EVALUATION OF THE EXTENT OF HMA MOISTURE DAMAGE IN WISCONSIN AS IT RELATES TO PAVEMENT PERFORMANCE

WisDOT Highway Research Study 0092-01-03

By

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16. Abstract: The objectives of this study were to evaluate the relationship between the performance of asphalt pavements in the field and the TSR values measured in the laboratory on the original asphalt mixtures used in constructing the pavements. In addition, the study included evaluating the effects of anti-stripping additives on field performance and their impact on the cost of the production and construction of the pavements. To assess the moisture damage problem in the field, a total of 21 existing WisDOT pavement sections that were built to meet the specification, prior to 1992, when the requirement of the TSR parameter was adopted, were selected to cover a wide range of locations and aggregate sources. The TSR data and the pavement condition data (PDI) for these projects were collected from the TSR database and the WisDOT Pavement Management Database, respectively. Analysis of this data indicated that there is no relationship between TSR and the field pavement performance as measured by the PDI reported in 2001. In addition, there was no relationship between the TSR and specific pavement distresses that are known to be related to the moisture damage (surface raveling and rutting). To evaluate the effect of using anti-stripping additive, a database study and a laboratory study were conducted. Results from the database showed that there is an effect of using anti-stripping additives on the pavement performance (as measured by PDI) and also an effect on the specific pavement distresses that are related to the moisture damage (surface raveling and rutting). In the laboratory, the anti-stripping additives were mixed with an asphalt binder, and the changes in binder properties were evaluated. Anti-stripping additives were not found to change the rheological properties of asphalt binders, nor to improve the rutting and fatigue related properties of asphalt binder as measured by the DSR. However, they were found to increase the adhesion of asphalt binder to selected mineral surfaces, especially when the binder bond is exposed to water. The cost estimation of the pavement with anti-stripping additives is found very similar to the cost of the pavement without anti-stripping additives when taking into consideration the cost of maintenance every 5-6 years of the pavement service life.

The recommendations from this study include considering either improvement of the TSR test or replacing the TSR procedure with other easier, less costly procedure. The improvement of the TSR testing protocol is needed to control the excessive variability that occurs during the standard procedure. Such improvements could lead to better quantifiable test and better correlation to the field pavement performance. It is further recommended that for a better assessment of causes and consequences of moisture damage of asphalt mixtures, the role of asphalt binder and aggregate should be studied separately by using adhesion and cohesion testing.

17. Key Words TSR, MOISTURE DAMAGE, PAVEMENT PERFORMANCE, PDI, RAVELING, RUTTING, ANTI-STRIPPING,	**18. Distribution Statement** No restriction. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road Springfield, VA 22161

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Executive Summary

Project Summary

The objectives of this study were to evaluate the relationship between the pavement performances in the field to the TSR values measured in the laboratory on the original asphalt mixtures. The effects of anti-stripping additives on asphalt mixtures and the additional cost of using additives on the production and construction of the pavement were also evaluated.

Background

Based on the moisture damage study, which was concluded in 1999, specific questions were raised about the meaning of the TSR values measured in the laboratory because of repeatability problems with the test and the lack of clear evidence of relationship between the TSR values and moisture damage in the field. The study did not identify any significant relationship between the conditions of the field test sites selected and the wide range of TSR values measured in the laboratory on original mixtures as well as re-fabricated mixtures.

As a follow up to that study, WisDOT and the industry in Wisconsin still questioned whether a relationship existed between failing TSRs and poor pavement performance. Based on the recommendation of the flexible pavements Technical Oversight Committee of, the Wisconsin Highway Research program (WHRP) funded a project to further investigate this issue and include more projects that did not inculed using anti-stripping additives and to investigate in more details the effect of anti-stripping additives. The University of Wisconsin – Madison, working with the Wisconsin DOT, conducted the study.

Process

To evaluate the relationship between the pavement performances in the field to the TSR values measured in the laboratory, a total of 21 existing WisDOT pavement sections, that were built to meet the specification prior to 1992 when the requirement of the TSR parameter was added, were selected to cover a wide range of locations and aggregate sources. The TSR data and the pavement condition data for these projects were collected from the TSR database (as developed by WisDOT central office laboratory in anticipation of the pending TSR specification implementation) and the WisDOT Pavement Management Database, respectively. Analysis of this data was conducted to determine the correlation between the TSR values and the overall pavement condition, as reported through 2001 by the Pavement Management Section. The pavement condition information as determined by the Performance Distress Index (PDI) and the individual pavement performance measures that are known to be affected by moisture damage were correlated to the TSR results of the selected projects. This analysis was used to determine if Wisconsin pavements exhibit a moisture damage problem. The moisture damage problem was defined based on selected performance indicators that include the following distress types: surface raveling, visible stripping and rutting, and/or alligator cracking.

To evaluate the relative change in performance and cost due to use of the additives, two sets of projects were studied. The first set included mixtures with aggregates that require anti-stripping additives. The other set included mixtures that used identical aggregates but without anti-stripping additive. The pavement condition data for these two sets of projects were collected to evaluate performance of the pavement when anti-stripping additive was used.

The most commonly used anti-stripping additive in Wisconsin was selected for evaluating the effect of additive on the asphalt binder properties in the laboratory. The Dynamic Shear Rheometer (DSR) device was utilized to measure different binder properties before and after using the additive at the required concentration. The project was expanded to study the effect of anti-stripping additives on adhesion and cohesion properties of asphalt binders to selected aggregates. To support this study, a new testing device, Pneumatic Adhesion Tensile Testing Instrument (PATTI), used by the Federal Highway Administration researchers, was modified and used to measure the adhesion properties of asphalt binder to selected types of aggregate surfaces, and the Tack Test System using the DSR was used to measure the cohesion properties of asphalt binder. The adhesion and cohesion properties are expected to be directly related to the moisture damage resistance of the binders.

The cost of using anti-stripping additive in the mixtures, the cost of TSR testing, and the cost of safety concerns when using additives were compared to the cost of early maintenance that could be required for repairing the pavement distress due to the moisture damage caused by lack of including anti-stripping additives.

Findings and Conclusions

The database analysis shows no clear relationship between TSR and the field pavement performance as measured by the PDI. Also, there is no relationship between the TSR and specific pavement distresses that are known to be related to the moisture damage (surface raveling and rutting). Analysis of the database however has shown that there is a positive effect of using anti-stripping additives on the pavement performance (as measured by PDI) and also an effect on the specific pavement distresses that are related to the moisture damage (surface raveling and rutting). In the laboratory study the binder measurements could not explain the trend in improvement of pavement performance observed in the database analysis. The anti-stripping additives were not found to change the rheological properties of asphalt binders, nor to improve the rutting and fatigue behavior of asphalt binder as measured by the DSR. However, these additives were found to have the effect of increasing the adhesion property of asphalt binder to selected mineral surfaces, especially when the binder bond is exposed to water. This laboratory result could explain the performance improvement detected in the field performance database.

The life cycle cost analysis of the pavement with anti-stripping additives is found to be very similar to the cost of the pavement without anti-stripping additives when taking into consideration the cost of maintenance every 5-6 years of the pavement service life.

Recommendations

The findings of this study shows that the current TSR protocol adopted by WisDOT cannot be used as a quantifiable measure of moisture damage effects on pavement performance. It can be used only as an index of compatibility between aggregates and asphalts. Therefore, if the argument that TSR results provide only an index is accepted, other tests that are easier to run, and most likely less costly, that could provide an index value with better repeatability should be used. Another alternative is investigating the improvement of the TSR testing protocol to control the various sources of variability that occurs during the test. Such improvements could lead to better quantifiable test and better correlation to the field pavement performance.

In this study it was found that there are test procedures for determining fundamental bonding properties of asphalt binders and aggregates. Such tests are needed particularly for evaluating the role of modified asphalts in enhancing adhesion properties. It is recommended that further research be continued to study the roles of asphalt binders and aggregates separately.

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CHAPTER ONE

INTRODUCTION

1.1 Background and Problem Statement

HMA Moisture damage is a problem that is not unique to Wisconsin. Nation wide the use of a test method to determine the potential of asphalt mixtures for moisture damage is used in specifications for highway construction.

In the early 1990s, the Wisconsin Department of Transportation (WisDOT) began to look at requiring the use of a test to predict the potential susceptibility of any given mixture to moisture damage and thus prevent possible associated pavement deterioration. At that time, the Tensile Strength Ratio (TSR) test (ASTM D-4867) was chosen, and the specification criterion required that when the TSR of a mixture at optimum %AC fell below 70%, the contractor was required to add an anti-stripping agent to the mixture. Additionally, if an anti-stripping agent was used, the new TSR value now had to meet or exceed a higher value of 75% (*1*).

Since the implementation of this requirement, a question has been raised as to whether the addition of the anti-strip agents, and the associated costs incurred from using this test has actually helped solve a problem that might not have even existed or has been accounted for by ensuing mixture and aggregate requirements. In 1997 a study was initiated to evaluate the effectiveness of the TSR test in measuring potential for moisture damage. The study, which was concluded in 1999 (Project # 0092-45-94), raised specific questions about the meaning of the TSR values measured in the laboratory due to test repeatability problems and the lack of clear evidence of a relationship between the TSR values and moisture damage in the field (*2*). The study did not identify any significant relationship between the conditions of the field test sites selected and the wide range of TSR values measured in the laboratory on original mixtures as well as re-fabricated mixtures. As a follow up to that study, WisDOT and industry still questioned whether a relationship existed between failing TSRs and poor pavement performance, and through the Wisconsin Highway Research program (WHRP) funded a project to further investigate.

1.2 Hypothesis

A relationship can be drawn to relate the pavement performance in the field to the TSR values measured in the laboratory on the original asphalt mixtures. This relationship could be used to justify the assumption that mixtures produced with or without anti-stripping additives, and with TSR values greater than 70% perform better than the mixtures with TSR values lower than 70%.

1.3 Research Objectives

The main objectives of this research are:

1. To determine if there is a relationship between the pavement performance measures that are known to be affected by moisture damage, and the TSR values measured in the laboratory on original mixes.
2. To evaluate the effects of anti-stripping additives on asphalt mixtures to determine if there is an effect on the pavement performance other than increasing resistance to moisture damage.

3. To estimate the additional cost of using additives, including the safety concerns and effect on production and construction cost of the pavement.

1.4 Research Methodology

The research methodology used is illustrated in Figure 1.1. It consists of the following main tasks.

Task 1: Selection of Pavement Sections and Collection of Data

A total of 21 existing WisDOT pavement sections, that were built to meet the specification prior to 1992 when the requirement of the TSR parameter was added, were selected to cover a wide range of locations and aggregate sources. The TSR data and the pavement condition data for these projects were collected from the TSR database (as developed by WisDOT central office laboratory in anticipation of the pending TSR specification implementation) and the WisDOT Pavement Management Database, respectively. Analysis of this data was conducted to determine the correlation between the TSR values and the overall pavement condition, as reported through 2001 by the Pavement Management Section.

Task 2: Assessment of the Moisture Damage Problem

The pavement condition information as determined by the Performance Distress Index (PDI) and the individual pavement performance measures that are known to be affected by moisture damage were correlated to the TSR results collected in Task 1 for the selected projects. This analysis was used to determine if Wisconsin pavements exhibit a moisture damage problem. The moisture damage problem was defined based on selected performance indicators that include the following distress types: surface raveling, visible stripping and rutting, and/or alligator cracking.

The analysis also included modeling to quantify the relationship between TSR values and quantitative measures of distress, and to determine the severity of the moisture damage problem and it's consequences on pavement performance.

Task 3: Comparative Performance and Cost of Additives

In this task the research team, in collaboration with the WisDOT staff, established an historical record of anti-stripping additives used, their cost, and amount specified in mix. To evaluate the relative change in cost due to use of the additives, two sets of projects were studied. The first set included mixtures with aggregates that require anti-stripping additives. The other set included mixtures that used identical aggregates but without anti-stripping additive. The pavement condition data for these two sets of projects were collected to evaluate performance of the pavement when anti-stripping additive was used.

The most commonly used anti-stripping additive in Wisconsin was selected for evaluating the effect of additive on the asphalt binder properties. The Dynamic Shear Rheometer (DSR) machine was utilized to measure different binder properties before and after using the additive at the required concentration.

The cost of using anti-stripping additive in the mixtures, the cost of TSR testing, and the cost of safety concerns when using additives were compared to the cost of early maintenance that could be required for repairing the pavement distress due to the moisture damage caused by lack of including anti-stripping additives.

Task 4: Expansion of Previous Study Implementation Plan

The project was expanded to study the effect of anti-stripping additives on adhesion properties of asphalt binders to selected aggregates. To support this study, a new testing device, Pneumatic Adhesion Tensile Testing Instrument (PATTI), used by the Federal Highway Administration researchers, was modified and used to measure the adhesion properties of asphalt binder to selected types of aggregate surfaces. The adhesion properties are expected to be directly related to the moisture damage resistance of the binders. The adhesion data was complied after different periods of exposure to water, and then analyzed.

Task 5: Final Report and Recommendations

In this task the results of tasks 1 and 2 were used to define the basis for recommendations regarding to the current requirement of the TSR in mix design acceptance. The results of task 3 and 4 were used to explain the value of using anti-stripping additives based on change in the pavement performance and estimated change in cost of production and maintenance.

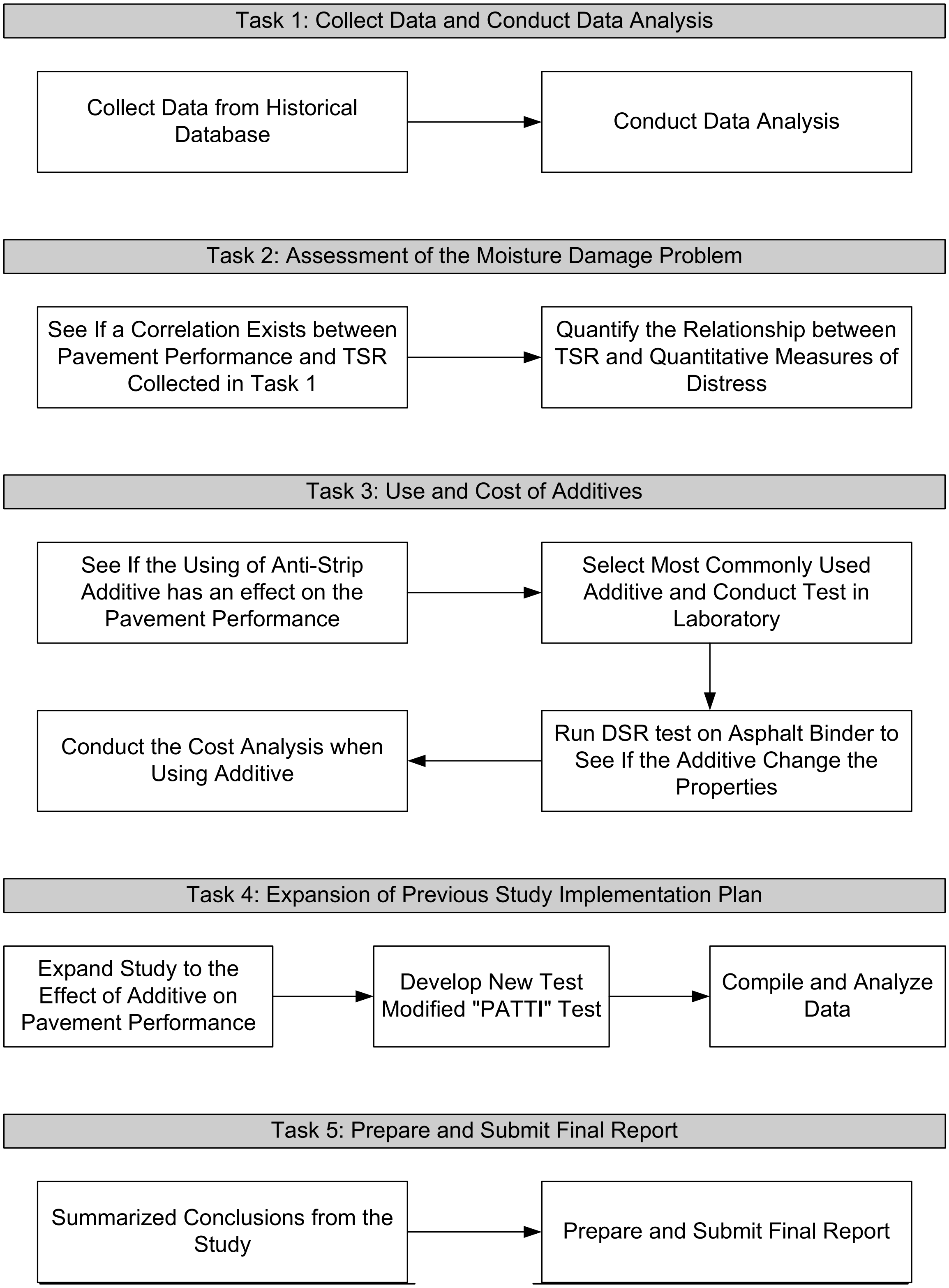


Figure 1.1 Research Methodology

1.5 Summary

This report is organized into five chapters. Chapter 1 includes the background, problem statement, objectives, research methodology, and research scope. Chapter 2 includes the database analysis, and the initial assessment of moisture damage problem based on the information from the database. It also provides the correlation between the prediction testing to evaluate the moisture susceptibility of the mixture (TSR) and the actual pavement performance in the field. Chapter 3 includes the results of the study to evaluate the effects of additives on pavement performance and also the effects on the asphalt binder properties. Chapter 4 contains the comparative life cycle cost analysis of using the additive in a typical pavement. Chapter 5 includes a summary of findings, the conclusions from this study, and the recommendations for future research.

CHAPTER TWO

ASSESSMENT OF MOISTURE DAMAGE PROBLEM

2.1 Introduction

This chapter is a summary of the research done to determine the relationship between the TSR values and the pavement performance for the existing WisDOT projects. The objective is to see if mixtures with TSR values below 70% can perform well in the field. Since the TSR is used to indicate the laboratory moisture damage, the correlations between the TSR and the pavement condition observed in the field should show how mixtures with low TSR perform in the field. In addition, the relationship between the source of aggregate that is used in the mixture and the pavement performance could provide an evaluation of the effect of aggregate mineralogy on pavement performance that is related to moisture damage.

2.2 Pavement Distress Index (PDI)

The results of a pavement surface distress survey are used to calculate the Pavement Distress Index (PDI). PDI is a mathematical expression for pavement condition rating keyed to observable surface distresses. The PDI of a section is a single number that summarizes the level of distress within the survey segment. PDI reflects the composite effects of various distress types and is used primarily for network-level evaluation with minor application to project-level analysis (*3*).

The analysis procedure used to compute PDI accounts for the relative importance of the various distress indicators by assigning appropriate distress factors (weighting factors). Each factor has ceiling constants for various levels of severity and extent as indicated in the PDI Survey Manual (*3*). The index is an algebraic result of the following expression:

$$\text{PDI (Asphalt Pavement)} = 100 \text{ x } (1\text{-}(\text{ALCR/BLCR x LCR x TCR x PT x FL x ER x SR x RT x LDT x TDT}))$$

ALCR/BLCR = Alligator/Block cracking	ER = Edge Raveling
TRC = Transverse cracking	SR = Surface Raveling
LCR = Longitudinal cracking	RT = Rutting
PA = Patching	LDT = Longitudinal Distortion
FL = Flushing	TDT = Transverse Distortion

2.3 Selection of Test Sections

The TSR database and the WisDOT Pavement Management Database were used to select the test sections. Projects built in 1992 were evaluated because it was the first year that TSR testing was evaluated without having a TSR requirement in the specifications. In other words, the mixture designs were used regardless of the resultant TSR value. The test sections from 21 WisDOT projects were selected (surface mixes only, and all without the use of anti-stripping additives). The selection criteria were based on the possibility to collect pavement performance data and to cover a wide range of TSR values. The projects were located randomly in Wisconsin as shown in Figure 2.1.

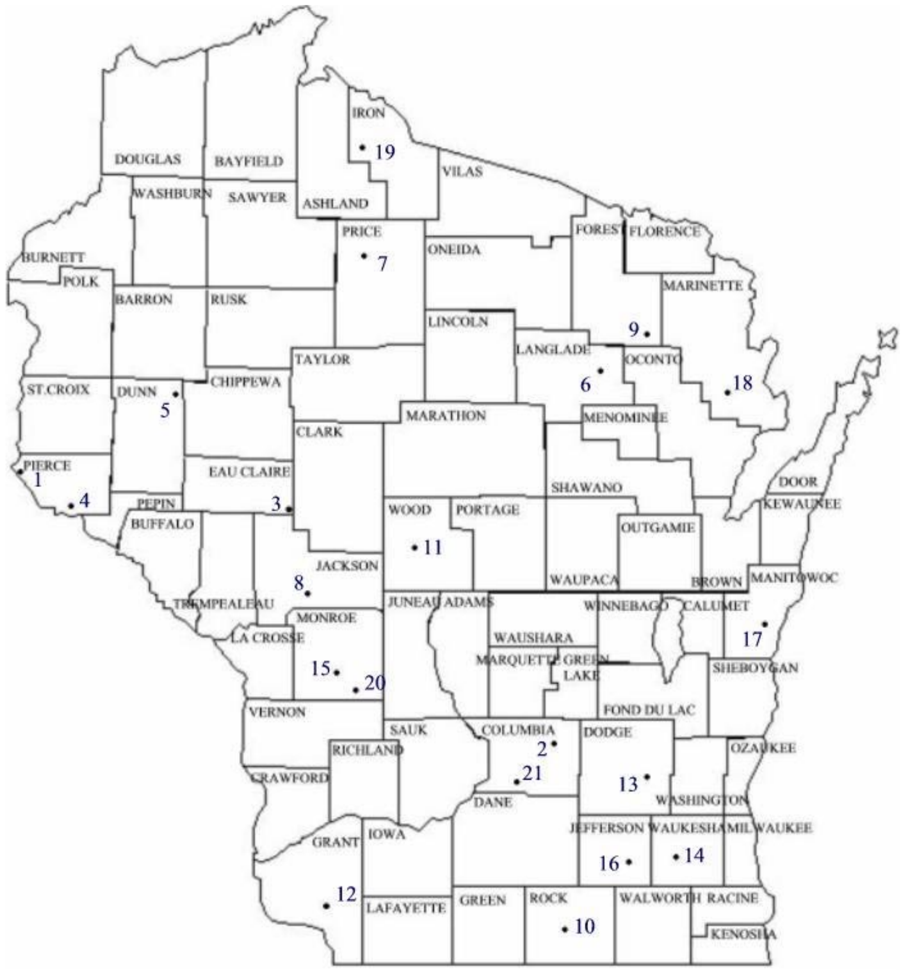


Figure 2.1 Location of 21 WisDOT Projects

2.4 Data Collection

For each project, the actual location of the test sections was identified with the help of the WisDOT representative. Subsequently, the WisDOT files and the Pavement Index File System (PIF) were searched to locate the Reference Points (RP) of the test sections for the particular project. These RP's were cross-referenced in the WisDOT Pavement Management Database to obtain PDI for the test section as a period of time. It is possible to identify PDI values for more than 10 sections on any one project.

Therefore, it must be noted that an average PDI for all sections was obtained for each project. In addition, the severity ratings of each type of pavement surface distress were collected from the WisDOT Pavement Management Database. Table 2.1 shows an example of data obtained for a selected project which includes the test sections with their severity rating of surface distresses, average PDI as a function of time, and the corresponding TSR values.

In this project the surface distresses that are known to be affected by moisture damage were correlated to the TSR values. These distresses include surface raveling and rutting. In the database, PDI and severity ratings for surface raveling and rutting vary during the pavement life; therefore, the increasing rate of PDI per year (ΔPDI / Year) and the average increasing rates of surface raveling and rutting were calculated and used in the analysis. This was done by dividing the total change in the values of the indicators between initial value and the last year of survey value by the number of years. It is recognized that the rate of change is not constant but it was assumed that the average value is the best indicator for this study. Table 2.2 shows the list of 21 test sections with their PDI rate, surface raveling rate, rutting rate and corresponding TSR values.

Table 2.1 Example of data obtained from selected project including test sections with the severity rating of surface distresses

Project No.	Age	Section	Block/ Allegator	Block Crack 1 - 24%	Block Crack 25 - 49 %	Block Crack 50-74 %	Block Crack 75 + %	Transverse Crack 1-5 STA	Transverse Crack 6-10 STA	Transverse Crack 11+ STA	Longitudinal Crack 1-100 STA	Longitudinal Crack 101-200 STA	Longitudinal Crack 201-300 STA	Longitudinal Crack 301 + STA	Patching Occasional	Patching < 10% of length	Patching 10 - 25 % of length	Patching > 25% of length	Flushing	Edge ravelling	Surface ravelling	Rut	Longi Distortion Crack 1-24 % length	Longi Distortion Crack 25-49 % length	Longi Distortion Crack 50 + % length	Trans Distortion Crack 1-24 % length	Trans Distortion Crack 25-49 % length	Trans Distortion Crack 50 + % length	PDI	PDI average	TSR
1331-05-74	1.5	I - 94E B-63	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7		
		STH 83S (END DIV)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7		
		OAKWOOD RD L	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7		
		BARK RIV STR	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	**7**	**76.2**
	3.5	I - 94E B-63	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	16		
		STH 83S (END DIV)	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13		
		OAKWOOD RD L	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13		
		BARK RIV STR	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	**13.75**	**76.2**

Table 2.2 Comparison of Lab TSR, PDI Increased Rate, Surface Raveling Increased Rate, and Rutting Increased Rate of 21 Projects

NO.	PROJECT#	PROJECT COUNTY	HWY#	TSR (TESTED VALUE)	PDI Increased Rate	Surface Raveling Increased Rate	Rutting Increased Rate
1	7182-03-71	Pierce	STH 35	38.7	6.03	0	0
2	1401-03-71	Columbia	STH 16	54.0	5.21	0	0
3	7030-09-71	Eau Claire	USH 10	47.8	12.47	0.167	0
4	7181-07-71	Pierce	STH 35	60.7	6.56	0.017	0
5	8111-02-71	Dunn	STH 64	55.3	6.33	0	0.213
6	9155-10-70	Langlade	STH55	59.5	12.6	0.33	0
7	1614-05-73	Price	STH 13	59.9	3.57	0.111	0.034
8	7062-03-71	Jackson	STH 27	65.2	4.82	0.094	0
9	9304-03-70	Forest	STH 101	60.6	7.26	0.042	0
10	1704-03-72	Rock	STH 11	60.8	10.36	0.167	0
11	1525-08-71	Wood	STH 73	79.0	4.51	0	0.103
12	1650-01-76	Grant	USH 61	64.2	4.44	0.0128	0.023
13	3031-02-71	Dodge	STH 67	65.9	5.08	0	0
14	1331-05-74	Waukesha	STH 83	76.2	2.26	0	0
15	5511-03-77	Monroe	STH 71	70.5	4.4	0.101	0
16	3082-00-71	Jefferson	USH 18	68.7	2.24	0	0
17	4100-06-72	Manitowoc	USH 151	78.9	9.51	0	0.2
18	1490-11-74	Marinette	USH 141	73.3	5.2	0	0
19	9250-07-70	Iron	STH 77	82.0	8.91	0.26	0.17
20	5134-08-71	Monroe	STH 131	86.0	3.32	0.08	0
21	5271-06-71	Columbia	STH 60	86.2	3.21	0	0

2.5 Data Analysis

2.5.1 Relationship between TSR and Pavement Performance

To correlate the TSR values with the PDI values a scatter plot was prepared as shown in Figure 2.2. It can be seen that there is no significant relationship between the TSR and PDI for these test sections. Linear regression analysis was used to fit a simple linear relationship which indicates a negative slope. This trend shows that higher TSR correlates with lower PDI rate, as shown in Figure 2.2. The R^2 value, however, is very low (0.126) which indicates that the relationship between these two parameters is not significant.

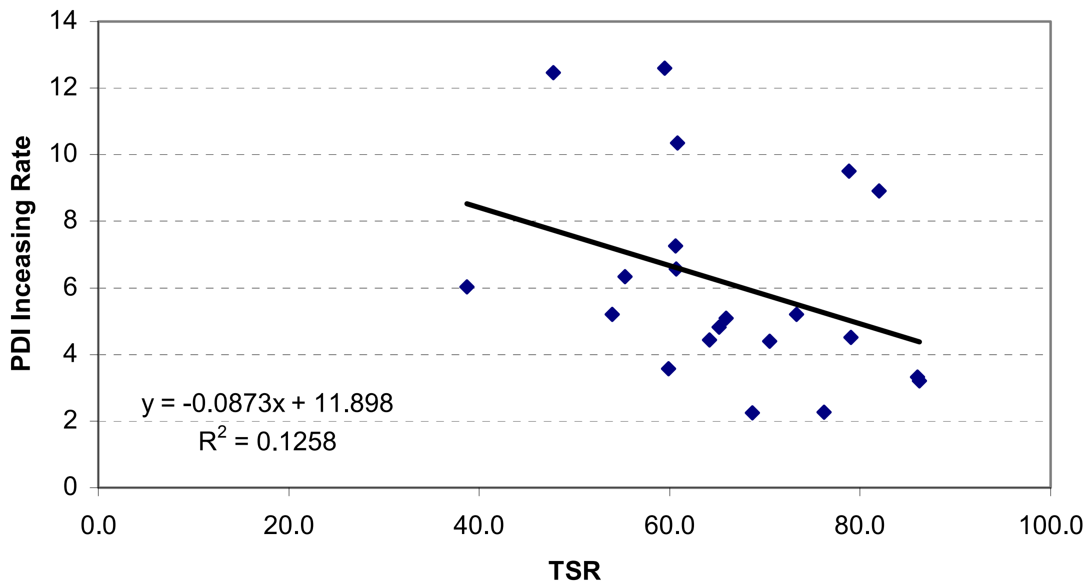


Figure 2.2 Relationship Between TSR and PDI Increasing Rate Per Year (ΔPDI / Year)

Since the PDI number is a collective indicator, it was decided to conduct more detailed analysis by relating the TSR values to the specific distresses known to be affected by moisture damage (rutting and raveling). The scatter plots for raveling and rutting versus TSR are shown in Figure 2.3 and Figure 2.4 respectively. The R^2 values in both figures do not show any significant relationship between TSR, surface raveling, and rutting. As a result, the TSR measured in the laboratory on original mixtures does not appear to correlate with the distresses that are believed to be affected by moisture damage in the field.

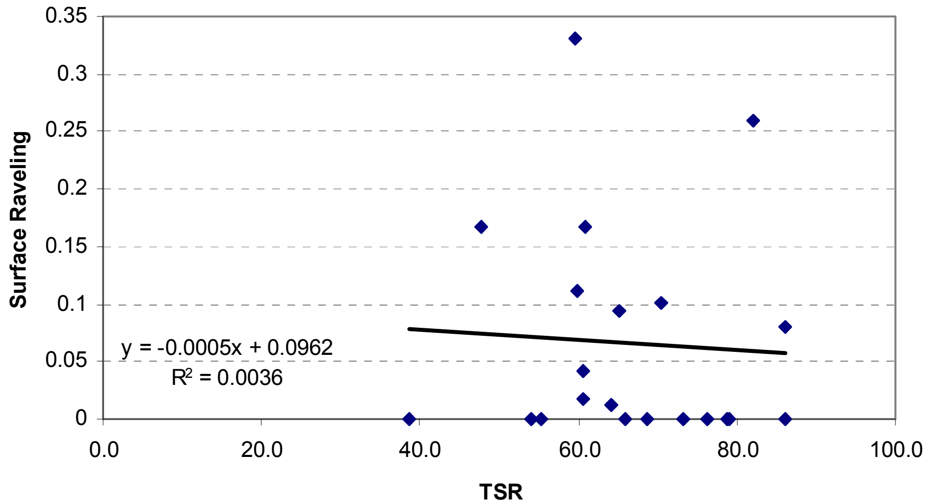


Figure 2.3 Relationship Between TSR and Surface Raveling

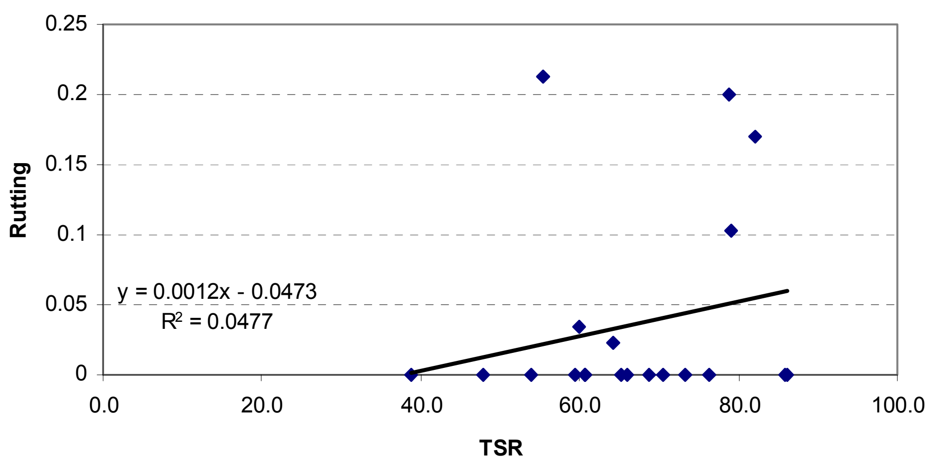


Figure 2.4 Relationship Between TSR and Rutting

2.5.2 Effect of Aggregate Mineralogy

The aggregate sources used in production of the HMA mixtures for these 21 projects contained different mineralogical compositions. The geological map of Wisconsin that shows the distribution of the bedrock in the state was used to locate and determine the mineralogy of different aggregate sources. A total of 9 predominant geological formations were identified in the State of Wisconsin with the assistance of the geologists at the Wisconsin Geological and Natural History Survey (WNHS) Department. This guideline was used to group the aggregate used in 21 projects as shown in Table 2.3.

Table 2.3 Geological Classifications of Wisconsin Aggregates

GEOLOGY CODE	DESCRIPTION
1	Platteville and Prairie Du Chein Dolomite
2	Platteville Dolomite
3	Galena Dolomite
4	Sinnippee Group (Both Galena and Platteville)
5	Silurian (Niagara Dolomite)
6	Prairie Du Chein Dolomite
6a	Pre-cambrian Crystalline Rock
7	Greenbay/Lake Michigan Glacial Lobes (Igneous + Carbonate) Dolomite
8	Langlade/Wisconsin Valley/and Older Glacial Deposits (Igneous Rocks)
9	Chippewa/St. Croix Older Gravel

Table 2.4 summarizes the aggregate sources for 21 projects and their corresponding aggregate mineralogy including the Geo Code. The effect of aggregate mineralogy on the pavement performance (PDI) is shown in Figure 2.5.

Table 2.4 List of Aggregate Sources and Corresponding Aggregate Mineralogy.

NO.	PROJECT#	PROJECT COUNTY	HWY#	AGG SOURCE	AGG MINEROLOGY	GEO CODE
1	7182-03-71	Pierce	STH 35	PRESCOTT QRY	Prairie Du Chien Dolomite	6
2	1401-03-71	Columbia	STH 16	KONE/RIO PIT	Igneous and Dolomite	7
3	7030-09-71	Eau Claire	USH 10	BOONE QRY	Precambrian Rock	6A
4	7181-07-71	Pierce	STH 35	PETERSON QRY	Prairie Du Chien Dolomite	6
5	8111-02-71	Dunn	STH 64	AMER.MTRLS#52	Prairie Du Chien Dolomite	6
6	9155-10-70	Langlade	STH55	DAVIS PIT	Igneous	8
7	1614-05-73	Price	STH 13	GUSTAFSON PIT	Chippewa Glacial	9
8	7062-03-71	Jackson	STH 27	ENDRES QRY	Prairie Du Chien Dolomite	6
9	9304-03-70	Forest	STH 101	MEYERS PIT	Igneous	8
10	1704-03-72	Rock	STH 11	BJOINS QRY	Platteville Dolomite	2
11	1525-08-71	Wood	STH 73	KORGER QRY	Precambrian Rock	6A
12	1650-01-76	Grant	USH 61	STANTON QRY	Galena Dolomite	3
13	3031-02-71	Dodge	STH 67	ULLMER PIT	Igneous and Dolomite	7
14	1331-05-74	Waukesha	STH 83	VULCAN/DOUSMAN	Igneous and Dolomite	7
15	5511-03-77	Monroe	STH 71	DONSKEY QRY	Prairie Du Chien Dolomite	6
16	3082-00-71	Jefferson	USH 18	DOUSMAN PIT	Igneous and Dolomite	7
17	4100-06-72	Manitowoc	USH 151	WAGNER PIT	Igneous and Dolomite	7
18	1490-11-74	Marinette	USH 141	GABRIEL PIT	Igneous and Dolomite	7
19	9250-07-70	Iron	STH 77	O'BRIAN LKE PIT	Chippewa Glacial	9
20	5134-08-71	Monroe	STH 131	O'ROURKE QRY	Prairie Du Chien Dolomite	6
21	5271-06-71	Columbia	STH 60	KLEMP PIT	Igneous and Dolomite	7

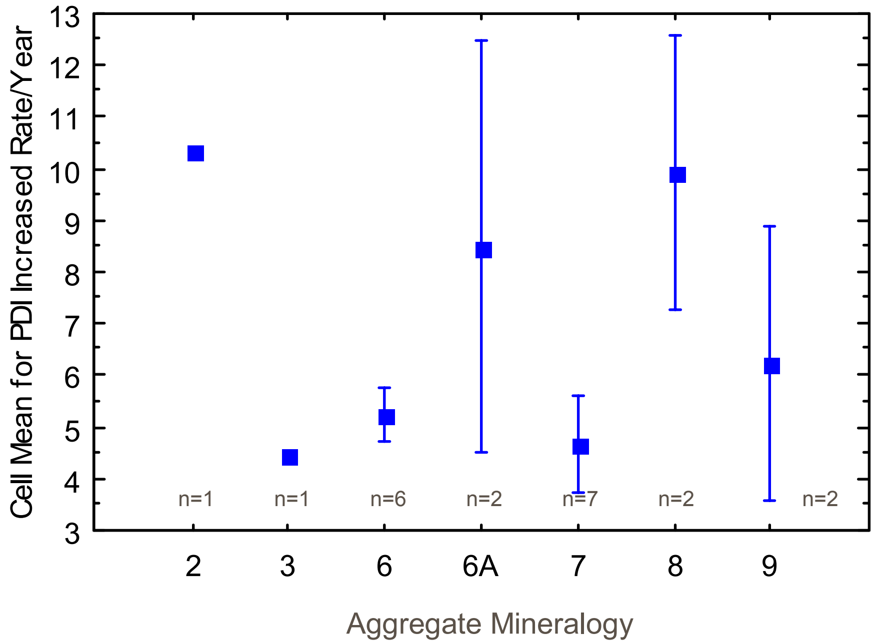


Figure 2.5 Effect of Aggregate Mineralogy on ΔPDI/Year

As shown in Figure 2.5, the aggregate with Geo code 2, 6A, and 8 show more change in PDI when comparing with the aggregate with Geo code 3, 6, 7 and 9. However, the scatter of the data is observed to be high even in some of the mineralogy (Geo code = 6A, 8, and 9) that has only two data points. Therefore, the graph could not clearly show a direct relationship between aggregate mineralogy and PDI values. This result could support the previous WisDOT research study, which mentioned that the mineralogy alone does not explain the moisture damage behavior, since the production and construction methods seem to have significant effect as well.

2.6 Summary

Based on the results presented in this chapter, which were obtained from the database analysis, the following points summarize the findings:

- There is no strong correlation between the TSR values and the field pavement performance (as measured by the PDI values). However, the data in 1992 was limited, and the data from other years cannot be used since 1992 was the only year that the TSR testing was considered without implementing the requirement for using anti-stripping additive.
- There is no correlation between the TSR values and specific pavement distresses that are known to be related to moisture damage (surface raveling and rutting). This raises some concerns regarding the value of the TSR test and its significance in predicting pavement damage due to moisture.
- Aggregate mineralogy could not clearly show a relationship to the pavement performance. This is to be expected since the pavement performance could be affected by several other factors such as the production and construction of the mixture, asphalt binder used, gradation, and other factors. This finding however, indicates that the mineralogy is not more important than the other factors and thus moisture damage due to mineralogy is not significant or important.

The above three points do not support the use of TSR values as a criterion for requiring anti-stripping additives because of the lack of relationship to pavement distresses or performance indicators. Since the WisDOT has required using these additives when TSR values are below 70%, it was prudent to proceed in the project to study the effects of these additives on the pavement performance. This is the subject of the next chapter.

CHAPTER THREE

EFFECT OF ANTI-STRIPPING ADDITIVES ON PAVEMENT PERFORMANCE

3.1 Introduction

In the proposal of this project, the research team planned on conducting field observation to evaluate and/or verify the effect of moisture damage problems on pavements with and without anti-stripping additives. Contacts with WisDOT technical staff and with contractors indicated that it is very difficult for the contractors to provide specific field locations of pavements that were constructed without the use of additives and with failing TSR values. Without such data the field surveys were considered ineffective. Therefore, the researchers, in agreement with the project Technical Oversight Committee, agreed to focus on studying the effect of anti-stripping additives on the pavement performance and on the asphalt binder properties. Analysis of the database was conducted to determine the effect of anti-stripping additives on asphalt pavement performance in the field. In addition, the most commonly used anti-stripping additives were mixed with an asphalt binder, and the changes in binder properties were evaluated in the laboratory. The PATTI (Pneumatic Adhesion Tensile Testing Instrument) was used for testing of the asphalt binders to measure the tensile adhesion strength of asphalt coating to various mineral surfaces before and after adding the anti-stripping additives. The PATTI device was recommended by FHWA, and has been used to study the moisture sensitivity of asphalt binders (*4*). The research team gathered information about types of additives used in Wisconsin and contacted the manufacturers to obtain samples of different additives. These additives were added to the asphalt binder at specified concentrations, and the testing of different binder properties was conducted in the laboratory.

3.2 Database Study

To establish the relationship between performance and the use of anti-stripping additives, specific aggregate sources that traditionally require anti-stripping additives in projects in Wisconsin were identified from WisDOT database. The PDI data for a large number of projects in which their aggregates were used was collected and the average rate of increasing PDI value per year (ΔPDI/year) was calculated for each project. The process of collecting PDI was similar to the data collection process mentioned in Chapter 2. The PDI values for these projects were compared to PDI values of projects in which the same set of aggregate sources, and/or other sources that are in the same group of aggregate mineralogy were used but without using anti-stripping additives.

The comparison of PDI values between the projects in which the same aggregate sources were used with and without anti-stripping additives is shown in Figure 3.1. The results show that using anti-stripping additive generally results in lower PDI values in most of aggregate types, especially the aggregate in the group of Precambrian Rock and Glacial Material (Geo code 6A, 7, and 8).

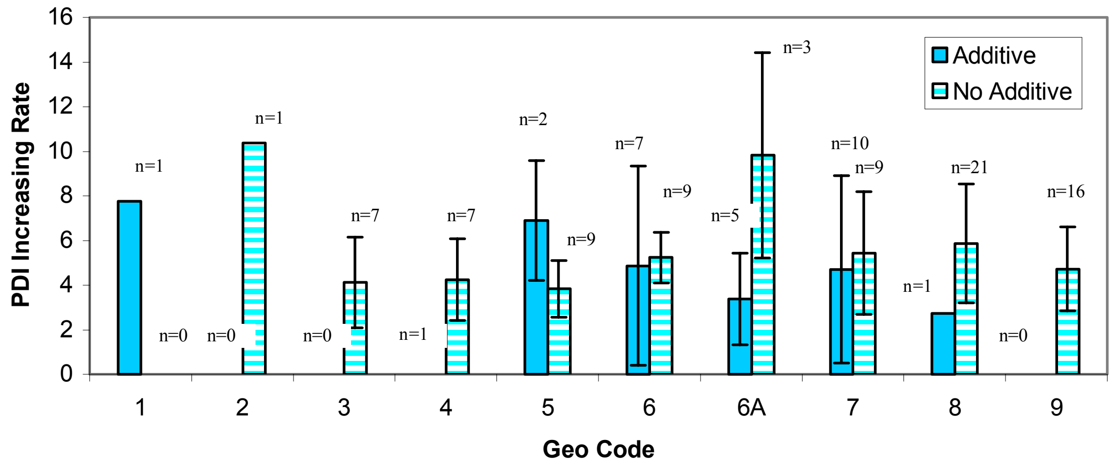


Figure 3.1 Effect of Anti-Stripping Additive on PDI

The effects on the surface raveling and rutting, when additives were used, were also determined and compared as shown in Figure 3.2 and Figure 3.3, respectively. The results shown in these figures indicate that using anti-stripping additives affects the increasing rate of pavement distresses that relate to the moisture damage in the field. Both graphs show that using the additive can reduce the severity of surface raveling and rutting in the field for most of aggregate mineralogy, except the Silurian (Niagara Dolomite) in Geo code 5, which shows higher severity when using additive. The results are correlated well to the effect of additive on PDI rate as shown in Figure 3.1.

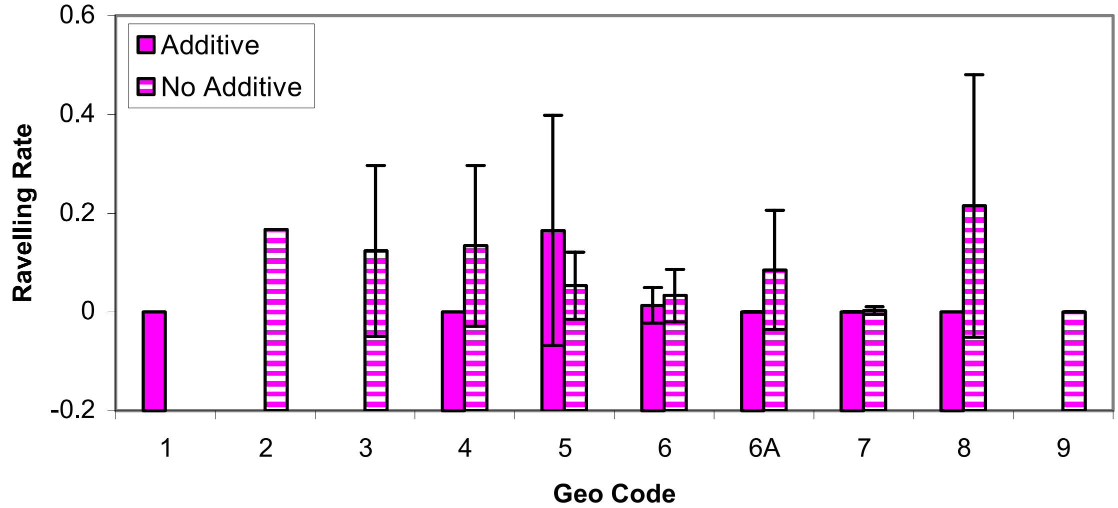


Figure 3.2 Effect of Anti-Stripping Additive on Surface Raveling

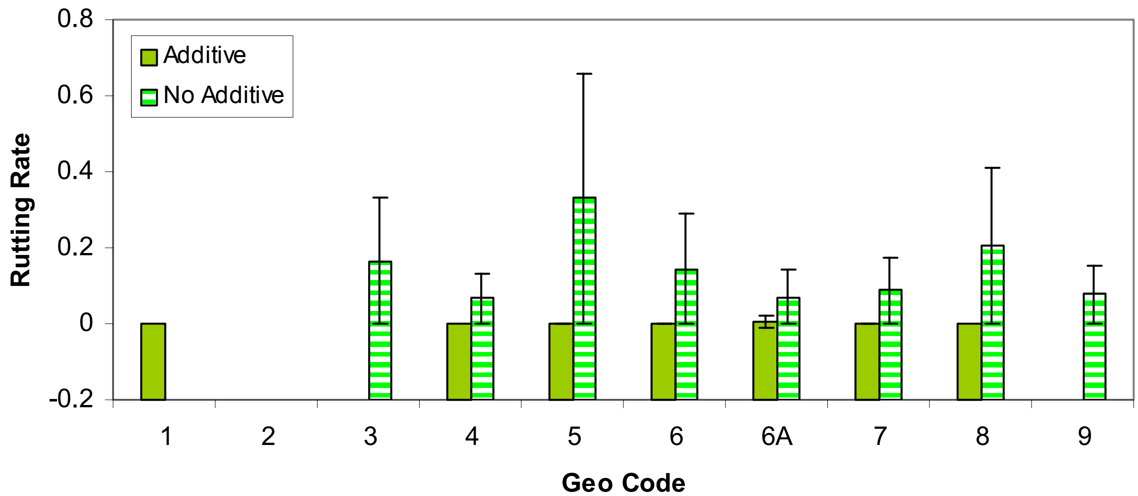


Figure 3.3 Effect of Anti-Stripping Additive on Rutting

3.3 Laboratory Study of Rheological and Damage Resistance Properties

The results from section 3.2 indicated that using anti-stripping additives has an effect on the pavement performance in the field. To test this finding, the anti-stripping additive was added in the asphalt binder. Then, different binder properties as related to the pavement performance were tested, including the adhesion property of asphalt binder. Adhesion is believed to be one of failure mechanism that causes the loss of bond between the asphalt and aggregate and leading to the stripping problem.

Anti-stripping additive manufacturer was contacted to provide a sample of additive used in Wisconsin. Morlife 3300 is the additive that was selected in this study since it is widely used in projects in Wisconsin. According to WisDOT's record, the additive was added to the asphalt binder in the amount of 0.5% by weight of asphalt at mixing temperature 135°C. The percent of additive used for this testing represents the most common amount used for this product. The following tests were performed to evaluate the effect of anti-stripping additive on the asphalt binder properties.

The dynamic shear rheometer (DSR) was used to measure visco-elastic properties, fatigue and rutting resistance at high and intermediate temperatures of the asphalt binder. The analysis presented in this section includes the comparison of the asphalt binder with and without anti-stripping additives using the complex shear modulus (G^*), storage modulus (G'), loss modulus (G''), and fatigue and rutting behavior as measured in the DSR.

3.3.1 Rheological Properties

The DSR is used to characterize the viscous and elastic behavior of asphalt binder at high and intermediate service temperatures. The complex shear modulus G^* and phase angle δ of asphalt binders are measured at the desired temperature and frequency of loading. Complex modulus G* is considered as the total resistance of the binder to deformation when repeatedly sheared. G* consists of two components: (a) storage modulus, G′, which is the elastic (recoverable) part, and (b) loss modulus, G″, which is the viscous (non-recoverable) part. The elastic component or storage modulus is related to the amount of energy stored in the sample during each testing cycle. The viscous component or loss modulus is related to the energy lost during each testing cycle through permanent flow or deformation.

For this testing, asphalt binders PG 58-28 with and without different kinds of additives were evaluated. The additives including Wetfix, Redicote, Morlife 3300, and Pavebond Lite were mixed with PG 58-28 in the amount of 1% by weight of asphalt. Based on the communication with the manufacturers, the amount range of additive between 0.5-1% can be added to the asphalt. The G′ and G″ of these binders were measured at intermediate and high temperatures (16C to 64 C). The DSR test was conducted at a frequency of loading of 1 Hz. The results of G′ and G″ are shown in Table 3.1. The ratio of G′ and G″ of PG 58-28 with additives to PG 58-28 without additive at different temperatures are shown in Figure 3.4 and Figure 3.5. The results indicate that all additives result in a reduction in G′ and G″ values with one exception (the Pavebond Lite). The reduction in G′ varies between ratio of 0.67 and 0.9. For the Pavebond Lite additive, there is essentially no effect on the G′ as ratio values are very close to 1.0. The G″ ratios are more similar when comparing different additives. The G″ ratios vary between 0.8 and 0.9 for three of the additives and between 0.95 and 1.1 for the Pavebond Lite. Since the repeatability of the DSR is known to be ±20%, It is very difficult to conclude that there is significant or important effect of any of the additives. It is clear however that for three of the additives (Wetfix, Redicote, and Morlife), the G*, G′, and G″ values of the binder are marginally reduced because of using additives.

Table 3.1 G′ and G″ of PG 58-28 without Additive and with Different Additives

Temp	Unmodified		Wetfix		Redicote		Morlife2200		Pavebond Lite	
	G'	G"	G'	G"	G'	G"	G'	G"	G'	G"
16	123726	268300	93087	221826	82204	244872	106829	247952	125373	294968
28	29150	98381	24570	89357	21523	81695	24736	88838	29642	98419
40	1702	13462	1323	11761	1227	10994	1376	11758	1586	12929
52	105	1977	82	1720	80	1624	87	1705	102	1870
64	12	408	10	361	11	344	11	363	13	379

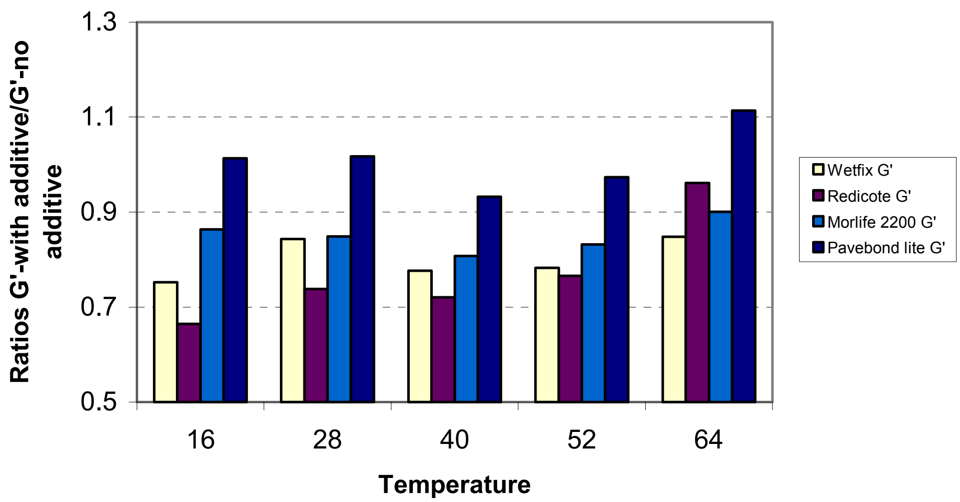


Figure 3.4 Relationship between Ratio of G′-with additive/G′-no additive and Temperature (°C)

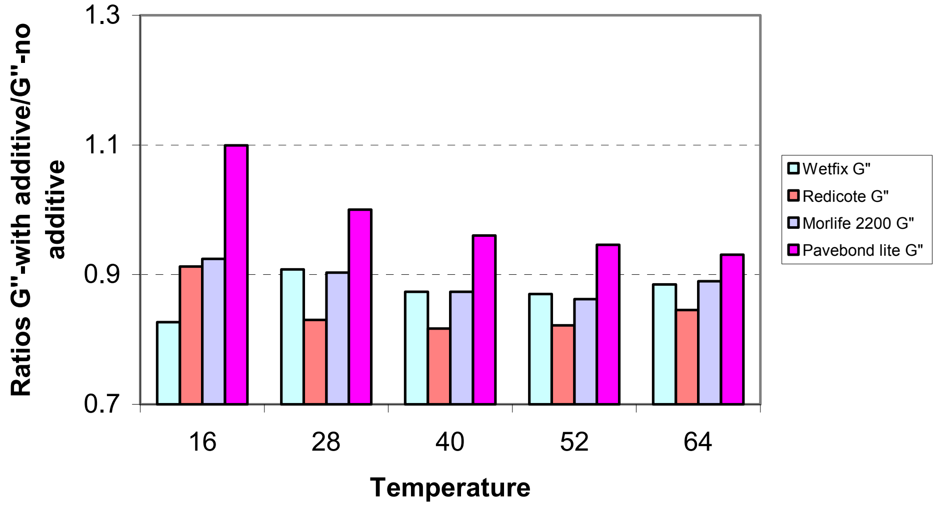


Figure 3.5 Relationship between Ratio of G″-with additive/G″-no additive and Temperature (°C)

3.3.2 Fatigue Resistance Evaluation

Fatigue damage is a distress mechanism observed in asphalt particularly at moderate to low temperatures. Under such conditions there appears to be a relationship between non-linearity, rate of energy dissipation, and fatigue damage. Preliminary studies have shown that unmodified asphalts are more sensitive to fatigue and that the use of modifiers in asphalt binders has shown dramatic improvement in the binder's response to fatigue (*5*). In this study, the modified asphalt binder (with anti-stripping additives) was evaluated to see if it could improve the fatigue resistance of the binders.

PG 58-28, and PG 58-28 mixed with 0.5% Morlife 3300 were tested at intermediate temperature at 13 °C, and at high and low stress levels. Figure 3.6 depicts plots for both asphalt binders and shows that fatigue behavior is very closed for both binders. The figure shows the ratio of dissipated energy (Rde) as a function of cycles of load application. The reduction in Rde is a sign of fatigue damage accumulation. The number of cycles to the start of reduction in Rde could be considered as the fatigue life (No. of cycles to failure). This findings, therefore, indicates that there is no significant difference in the fatigue resistance for both asphalt binders.

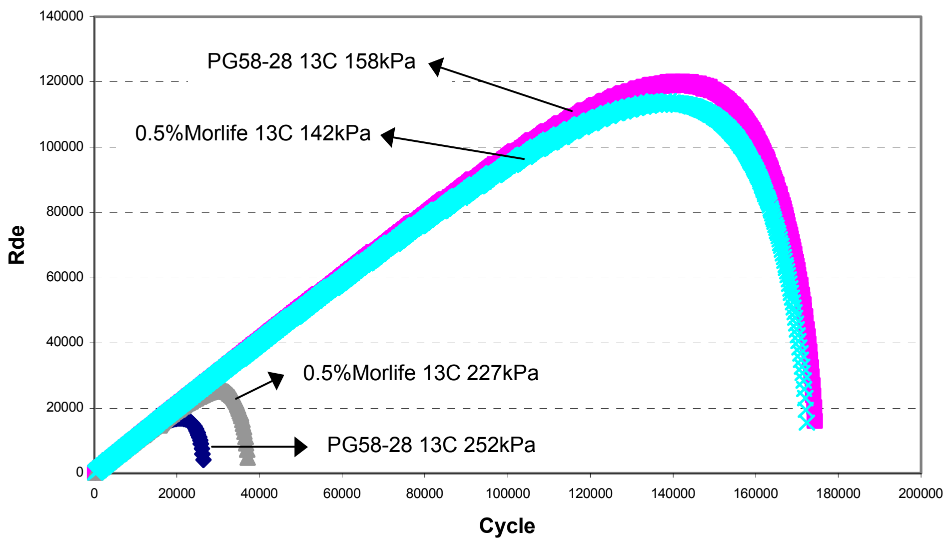


Figure 3.6 Rde Vs. Cycle Comparison Chart (Intermediate temperature at 13 °C)

3.3.3 Rutting Resistance Evaluation

Rutting is caused by accumulation of permanent deformations caused by the repeated application of traffic loading. By carefully selecting the loading time periods, traffic speed can be effectively simulated or represented. By selecting a certain range of stress on the asphalt samples, different traffic loading conditions can be simulated. The accumulated permanent deformation (strain) during each cycle of loading and the rate of the accumulation as a function of cycles provide useful information to evaluate the rutting resistance of the asphalt binders.

In this study, the same anti-stripping additive which is 0.5% Morlife 3300 was added to binder (PG 58-28) and then tested at high temperature (58 °C) to compare the rutting resistance between the modified asphalt binder with additive and unmodified asphalt binder. The measurements include accumulation of permanent strain as a function of cycles. The results of testing are illustrated in Figure 3.7. The plots show that the asphalt without additive performs better than the asphalt with additives as related to the rutting resistance. However, the difference between the two asphalts is not significant. Therefore, the only conclusion that can be made is that the additive does not appear to improve the rutting resistance of the original asphalt binder.

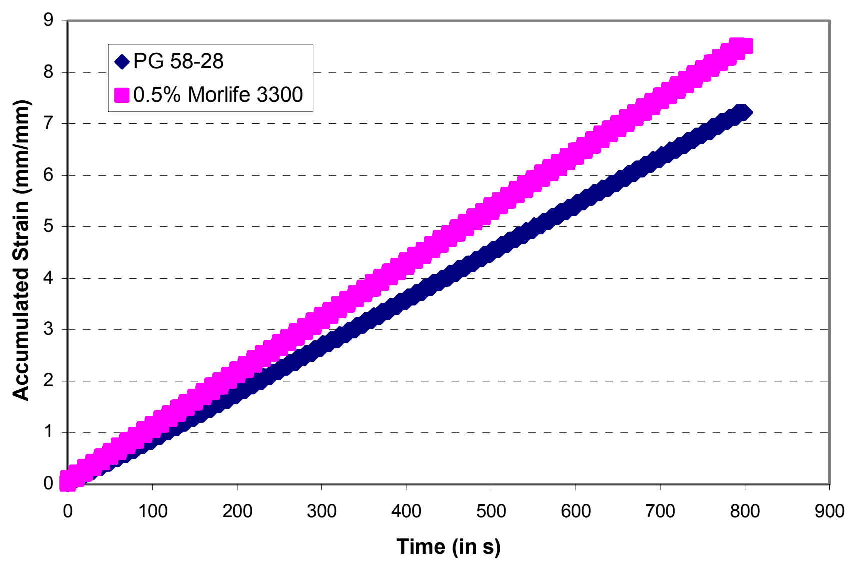


Figure 3.7 Accumulated Strain (mm/mm) Vs. Time

3.4 Adhesion and Cohesion Testing

From the study of rheological and damage characterization testing, it is clear that such test methods are not suitable to evaluate effects of anti-stripping additives. In order to explain the improvements in performance observed from the PDI database, it was necessary to find other testing procedures that could explain this behavior. Literature in the field of adhesives and paints was searched to explore methods used in these fields. Two tests were selected: an adhesion test and a cohesion test and were conducted to study effects of various additives. The following sections cover the findings from literature review and the testing conducted for this project. As shown, better understanding of effect of additives has been achieved.

3.4.1 Literature Review Regarding Adhesion Measurements

3.4.1.1 The Mechanism of Adhesion in Asphalt-Aggregate Systems

For asphalt-aggregate systems, many theories have been suggested to explain the adhesion phenomenon. Based on reviews by Rice (1958) (*6*), we can identify four major concepts as shown in Table 3.2 to explain adhesion mechanism.

Table 3.2 Summary of the Theories Used to Explain the Mechanism of Adhesion in Asphalt-Aggregate Systems

Theory	General Principle	Supporting Researchers
Mechanical Theory	Asphalt is forced into the pores and irregularities of the aggregate surface, providing the mechanical interlock.	Knight 1938 (*7*), Lee and Nicholas 1954 (*8*), and Rice 1958 (*6*)
Chemical Reaction Theory	Chemical reaction occurs between the adsorbed asphalt and the constitutes of the aggregate phase.	Rice 1958 (*6*) and Maupin 1982 (*9*)

Molecular Orientation Theory	Asphalt molecules orient themselves so as to satisfy the energy demands of the aggregate surface to the maximum of their capacity.	McBain and Lee 1932 (*10*), and Mack 1957 (*11*)
Interfacial Energy Theory	Adhesion is a thermodynamic phenomenon related to the surface energy of the materials involved (asphalt, water, air, and aggregate)	Thelen 1958 (*12*), Ishai and Craus 1977 (*13*)

3.4.1.2 Theories to Explain the Stripping Phenomenon

Since moisture damage was reported as a key distress affecting asphalt pavements, researchers have conducted basic studies on adhesion-tension at the asphalt aggregate surface and applied the principles of the surface chemistry and physics to understand the stripping phenomenon. These studies have resulted in the proposition of various stripping theories and the development of several laboratory tests to quantify the degree of propensity of the asphalt mixes to moisture damage. Table 3.3 summarizes the theories by which researchers have explained the phenomenon of stripping in asphalt mixes. These theories generally indicate that moisture damage occurs in the presence of water and pore pressure, and is influenced by the properties of aggregates and asphalt. Highway engineers are aware of the fact that moisture damage is influenced by the aggregate and asphalt properties in presence of water. They look for practical techniques to identify the onset of moisture damage problems in a pavement and the methods by which the interference of water with the asphalt-aggregate bond can be prevented. None of the theories listed in Table 3.3 could singly explain the phenomenon of field moisture damage due to the variability in highway materials, environment, construction practices, and evaluation methods, since there are complex interactions among these different main factors.

Table 3.3 Summary of the Theories Used to Explain the Stripping Phenomenon

Theory	General Principle	Supporting Research Source
Contact Angle Theory or Mechanical Adhesion Theory	Asphalt is displaced because the contact angle of water is less than that of asphalt.	Taylor and Khosla 1983 (*14*), Stuart 1990 (*15*), and Hicks et al. 1991 (*16*)
Theory of Interfacial Energy or Molecular Orientation Theory	Asphalt molecules are displaced from the aggregate surface because the surface energy of water is less than that of asphalt.	Taylor and Khosla 1983 (*14*), Stuart 1990 (*15*), and Hicks et al. 1991 (*16*)
Chemical Reaction Theory	Changes in the pH value of water around the aggregates affect the microscopic water at the mineral surface leading to the build-up of opposing, negatively-charged, electrical double layers on the aggregate and asphalt surfaces.	Taylor and Khosla 1983 (*14*), and Hicks et al. 1991 (*16*)
Pore Pressure or Hydraulic Scouring Theory	Pore pressure of water entrapped due to mix densification under traffic results in increased pore pressure on the asphalt films, leading to rupture of the asphalt films.	Taylor and Khosla 1983 (*14*), Hicks et al. 1991 (*16*), and Kandhal 1994 (*17*)
Theory of Spontaneous Emulsification	Adhesion between the asphalt and aggregates is lost due to the formation of an inverted emulsion.	Taylor and Khosla 1983 (*14*), and Hicks et al. 1991 (*16*)

3.4.1.3 Measurement of Adhesion

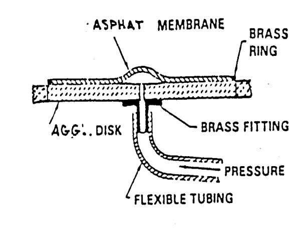
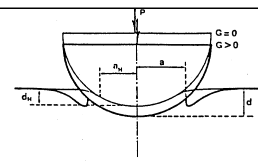
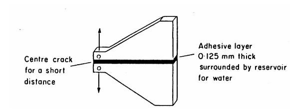
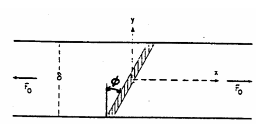
The term "work of adhesion" has been used in two different ways: 1) to refer to the energy obtained when the surfaces join, and 2) to refer to the amount of energy needed to break the bond. The values of these two energies, although related, are not the same. As a result of the remarkable advancement in fracture mechanics theories, the latter type of energy, that required to break the joint, has been considered a more accurate term (*18*).

In the existing adhesion and disbonding literature, the methods used to measure the strength of adhesive joints may be generally divided into three different groups: qualitative, semiquantitative and quantitative. To study the complex asphalt-aggregate systems and to relate their adhesion-disbonding properties to pavement performance, a quantitative method is necessary. Previous research is rich with all types of qualitative and semiquantitative methods that are, unfortunately, not very successful in developing a relation between adhesion properties of the asphalt-aggregate system and the pavement performance.

3.4.1.4 Adhesion Testing Techniques in Other Related Field

A large number of test methods have been developed for the quantitative evaluation of adhesive joints. An extensive review of these methods resulted in the selection of only four methods that are seen to be practical, simple, and promising for the evaluation of the adhesion phenomena in the asphalt-aggregate systems. While none of these methods is known to have been used before, they have been used to study polymeric adhesives used to bond different types of material, including metals, glass, or plastic composites. A brief description of each method is presented in Table 3.4.

Table 3.4 Summary of Adhesion Test Method in Other Fields

Method	Description	Configuration
Blister (Blow-Off) Adherometer (SHRP Binder Program 1991)	Air or water pressure is applied, then the blister height is measured. The pressure and height can be related to the fracture energy of adhesive bond. However, this method is very difficult to use.	
Double-Cantilever Beam (DCB)	Adhesive is applied between two identical plates of adherend, then a force is applied at one end to separate the plates. Force is measured and related to fracture energy, crack propagation rate, or strength of bond.	
Spherical Indenter Adherometer (SIA) (Hertz 1881 [*19*], Johnson and Kendall 1971 [*20*])	Theory of the contact between a rigid sphere and an elastic half space. Actual contact area under a given load minimizes the total energy of the system.	 Difference in contact area and penetration as caused by the attractive forces.
Scarf Test (Trantina 1972 [*21*])	Consider the concept of type 1-failure occur within adhesive (cohesive failure), and type 2-fracture plane is forced to shift to the interface or to the adherend. Fracture energy is much larger under type 2 than type 1.	 A Scarf Joint ϕ = scarf angle

Except for the Blister test, the other three techniques were not found to be practical enough to be used for asphalts. During the Strategic Highway Research Program (SHRP), the Blister test was identified as a possible useful test, and then a prototype device was developed for evaluation. The complexity of the system put a quick end to the development and the concept was found not practical.

3.4.1.5 Pneumatic Adhesion Tensile Testing Instrument (PATTI)

The Pneumatic Adhesion Tensile Testing Instrument (PATTI) was initially developed by the National Institute of Standards and Technology (NIST) and has been recently utilized by Youtcheff (1997) to evaluate the adhesive loss of asphalt-aggregate systems exposed to water (*4*). The PATTI 110 used in this study is referred to as the ASTM D 4541 (*22*), "Pull-Off Strength of Coatings using Portable Adhesion Testers". The PATTI device and its cross-section schematic drawing of the piston are shown in Figure 3.8 and Figure 3.9. The main features of this device include a portable pneumatic adhesion tester, a pressure hose, a piston, and a metal wing-pull stub as a loading fixture.

To perform a test, air pressure is transmitted to the piston which is placed over the pull stub and screwed on the reaction plate. The air pressure induces an airtight seal formed between the piston gasket and the aggregate surface. When the pressure in the piston exceeds the cohesive strength of the asphalt or the adhesive strength of the asphalt/aggregate interface, the failure of specimen occurs. The pressure at failure is recorded and then converted into the pull-off tensile strength (kPa) (*4*).

The advantage of the PATTI device is that it allows: 1) using an aggregate surface, 2) conditioning specimen in water after applying asphalt between pull stub and aggregate surface, and 3) observing the failure surface to define adhesive versus cohesive failure. In addition, the device is low cost, simple, and well described by an ASTM standard procedure. The PATTI is therefore considered as a good test for measuring adhesive characteristic before and after water conditioning.

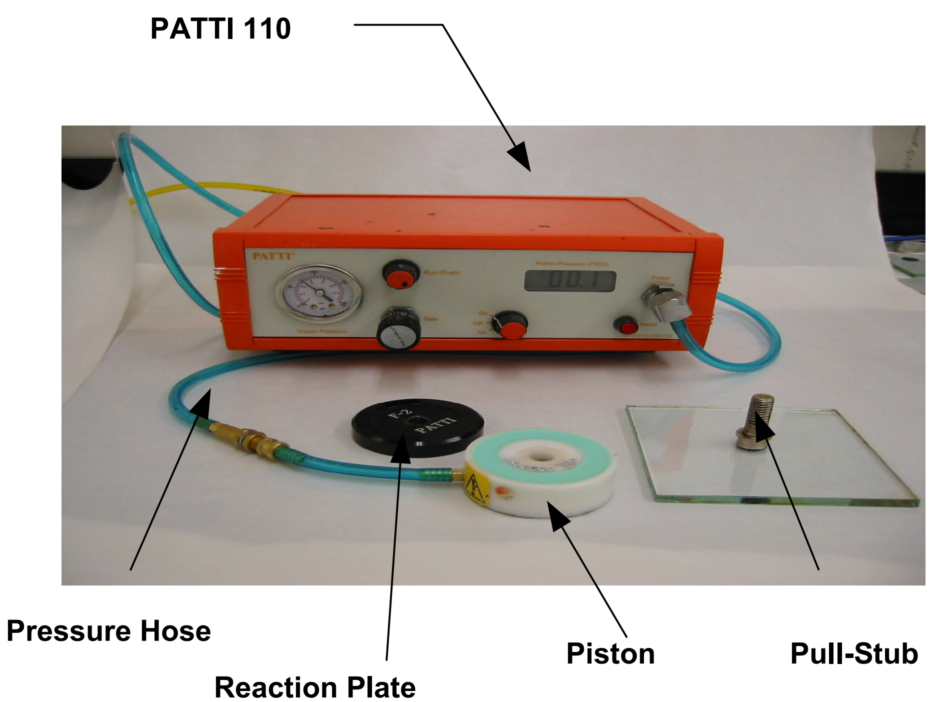


Figure 3.8 Main Features of PATTI 110

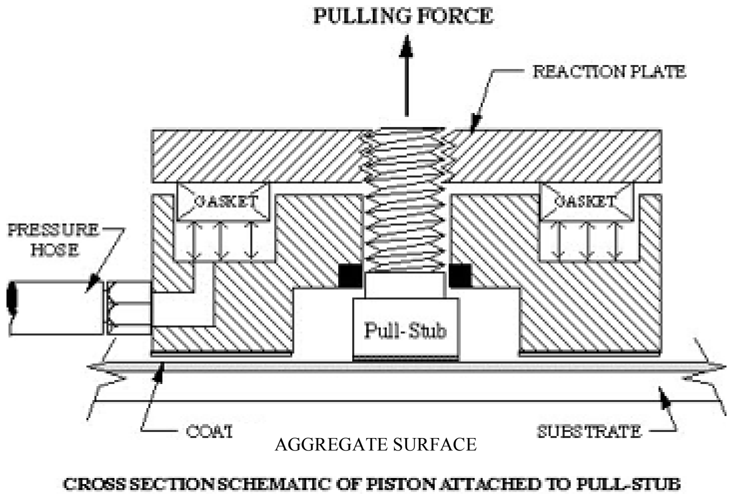


Figure 3.9 Schematic Drawing of PATTI 110

3.4.2 Adhesion Testing

Adhesion testing of asphalt binder can evaluate the role of the binder in affecting moisture sensitivity of mixtures. Specifically, water is believed to affect asphalt adhesion due to diffusion or solvation effects. Petersen conducted an infrared study of hydrogen bonding in asphalt (*23*). He stated that when a thin film of maltenes coating a glass plate was soaked in water, the water altered the nature of its hydrogen bonding, thus indicating that water was incorporated into its structure. Under the Strategic Highway Research Program (SHRP) efforts to develop a blister test were initiated but proved unsuccessful (*7*). Toward the end of SHRP, researchers at the National Institute of Standards and Technology (NIST) advanced the pneumatic adhesion tester for evaluating the adhesive loss of asphalt-aggregate systems exposed to water (*9*). The purpose of this section is to report the results of evaluating the effect of moisture on the asphalt binder and the significance of using anti-stripping additive in the binder to resist moisture effects on binder adhesion.

3.4.2.1 Experimental Procedure

The experimental procedure includes measuring the tensile and bonding strength of asphalt binder applied to a solid surface as a function of the time sample is exposed to water. Asphalt binder is applied to a pull stub, which is then pressed onto the solid surface. Glass plate and various types of aggregate surface were used as the adherend to see the effect of porous surface on the adhesion. The pressure necessary to debond the conditioned specimen at 25 °C is measured with a pneumatic adhesion tester. Table 3.5 shows the experimental design for the adhesion test of asphalt binder with and without anti-stripping additive (Yes or No) to the glass plate and the aggregate surface (Platteville, Galena, Silurian, or Prairie Du Chein Dolomite). The water conditioning was done for different time intervals (0, 6, 24, 48 hours).

Table 3.5 Experimental Design for Adhesion Testing

Conditioned Time in Water (hrs)	Glass (GL)		Platteville (P)		Galena (G)		Silurian (S)		Prairie Du Chein (PDC)	
	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
0	GL0-N	GL0-Y	P0-N	P0-Y	G0-N	G0-Y	S0-N	S0-Y	PDC0-N	PDC0-Y
6	GL6-N	GL6-Y	P6-N	P6-Y	G6-N	G6-Y	S6-N	S6-Y	PDC6-N	PDC6-Y
24	GL24-N	GL24-Y	P24-N	P24-Y	G24-N	G24-Y	S24-N	S24-Y	PDC24-N	PDC24-Y
48	GL48-N	GL48-Y	P48-N	P48-Y	G48-N	G48-Y	S48-N	S48-Y	PDC48-N	PDC48-Y

N: No additive
Y: With Additive

3.4.2.2 Specimen Preparation

Asphalt binder PG 58-28 was used, and the 0.5% Morlife 3300 was selected as the anti-stripping agent in this test. Aggregate surfaces were obtained from cutting the rock to provide a smooth surface of aggregate. These rocks were obtained from the Geology Department at UW-Madison, with the required mineralogy corresponding to the mineralogy sources stated in Chapter 2.

The aggregate and glass surface was prepared by rinsing repeatedly with distilled water followed by acetone, and allowed to dry prior to use. As a means for controlling the film thickness, two pieces of 1/4″ x 1/4″ x 2 1/2″ metal blocks were put under the pull stub. The space between the stub surface and the aggregate/glass surface is the film thickness of asphalt specimen (Figure 3.10)

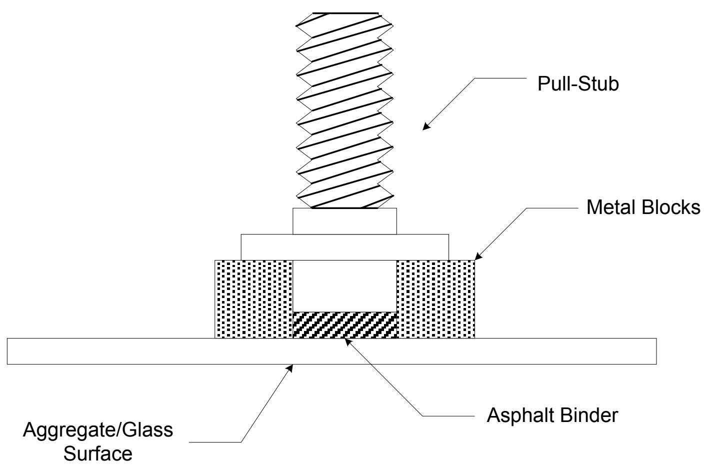


Figure 3.10 Specimen Preparation

The asphalt is heated to 100-145 °C, and then applied to the stub, which is then pressed onto the aggregate/glass surface. Prior to use, the stubs and aggregate/glass surface were heated to 65 °C by a heat gun. The literature (*8*) indicated that the excess asphalt around each specimen did not affect the pull-off strength, and so it was not removed. Specimens were set at room temperature for 24 hours before testing or conditioning in water. Conditioned specimens were submerged in the water at 25 °C, taken out from the water at certain periods of time (6, 24, and 48 hours), and immediately tested.

3.4.2.3 Results and Analysis

` The results of testing can be classified into two modes. When failure occurs at the interface between asphalt and aggregate surface, it is called an Adhesion failure (A). When failure occurs within asphalt film, it is assumed that bond strength was greater than cohesive strength of asphalt and thus failure is a Cohesion failure (C). Figure 3.11 depicts an example of each of these failure types.

Cohesion Failure **Adhesion Failure**

Figure 3.11 Type of Failure from the Adhesion Test of Asphalt Adhered to Aggregate Surface

Table 3.6 shows the results of adhesion test in term of the average pull-off strength. The failure mechanism of the specimens whether it was cohesion or adhesion failure is also shown in the table. As can be seen, the results vary between the types of aggregate source used. All unconditioned specimens show the cohesive failure (C), which means that failure occurred within the asphalt layer. The adhesion failure (A) is found in the conditioned specimens as early as six hours of conditioning. In the adhesion failure, the bond between the asphalt and aggregate is broken. The conditioning of specimens in water also shows a significant variation in the failure mechanism and the ultimate pull-off strength. It can be seen that after 48 hours of conditioning, all failures were in adhesion (A) with the exception of the glass plate, which is non-porous material. It is also clear that the Galena aggregate source shows the lowest pull-off strength, while the PDC shows the highest. In all cases, the use of additive appears to increase the pull-off strength. Figure 3.12 shows the effect of anti-stripping additive and time conditioning in water to the pull-off strength of different aggregates and glass surface.

Table 3.6 Pull-off Strength of Asphalt Binder Testing

Conditioned Time in Water (hrs)	Glass (GL)		Platteville (P)		Galena (G)		Silurian (S)		Prairie Du Chein (PDC)	
	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
0	1982 C	1571 C	1095 C	1140 C	873 C	810 C	1067 C	1203 C	1306 C	1284 C
6	2482 C	2207 C	718 A	912 C	256 A	291 A	655 A	806 C	1004 C	1557 A
24	2488 C	1977 C	603 A	880 A	350 A	378 A	638 A	901 A	697 A	1126 C
48	2134 C	1872 C	652 A	645 A	284 A	460 A	592 A	820 A	592 A	817 A

*C = Cohesion Failure, A = Adhesion Failure

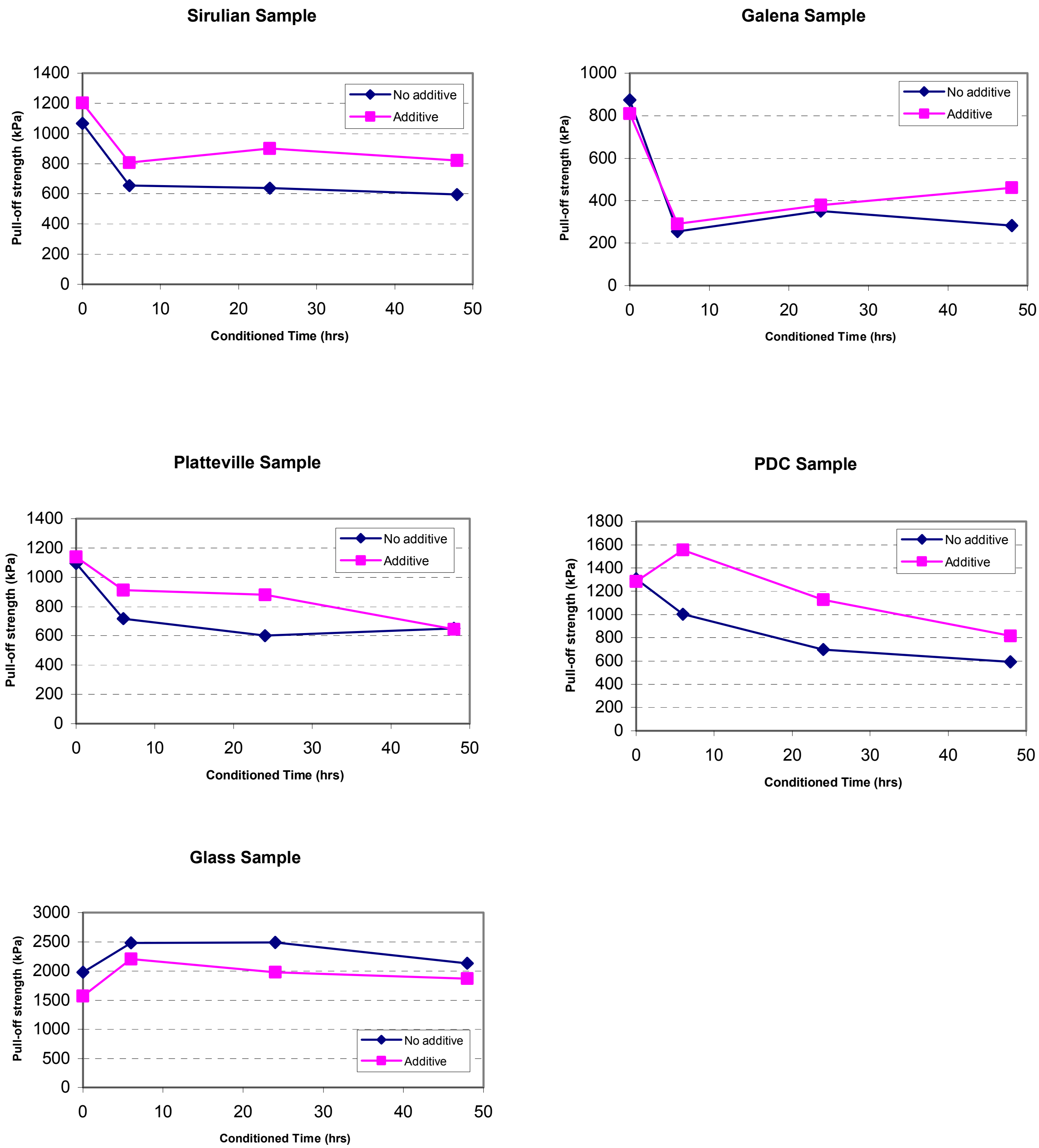


Figure 3.12 Effect of Additive and Time Conditioning in Water to the Pull-Off Strength of Sirulian, Galena, Platteville, PDC, and Glass Plate Samples

The graphs from Figure 3.12 show that the use of additive results in higher pull-off strength for all aggregate samples (Sirulian, Galena, Platteville, and PDC). And the pull-off strength tends to decrease as the time conditioning in water increases. Meanwhile, the samples testing with the glass plate show lower pull-off strength value when using the additive, and there is no significance of the conditioning time. These findings are as expected, since the water is believed to be able to penetrate into aggregate which is the porous material, and hence weaken the bond between asphalt-aggregate interface. The longer the conditioning time in water, the lower the pull-off strength value. The water cannot penetrate into the interface between asphalt and glass plate, therefore, the results do not show any effect of the additive and time conditioning in water for the glass plate.

To quantify the effects, statistical analysis was performed to evaluate the significance of the controlled variables on response effects. The three-way ANOVA was selected to evaluate how the response variable, which is the pull-off strength, is influenced by the three independent variables which are aggregate types, additive used, and time conditioning in water. By considering the F-distribution at significance level of 0.05, Table 3.7 shows the significance of main effects and interaction effects for each factor in the model.

Table 3.7 3-Way ANOVA Output

Effect	DOF	F distribution	P-value
Aggregate	3	42.562	0.000*
Additive	1	19.477	0.000*
Time	3	32.588	0.000*
Aggregate*Additive	3	2.087	0.116
Aggregate*Time	9	3.225	0.005*
Additive*Time	3	1.891	0.146

* Significant effect

The results indicate that the main effects of aggregate types, additive, time conditioning in water, and the interaction between aggregate and time conditioning in water to significantly affect the pull-off strength. As shown in Figure 3.13, Galena gives lower pull-off strength than other aggregate types, whereas testing the adhesion with PDC gives the highest pull-off strength. The Sirulian and Platteville obtain the closed value of pull-off strength. Figure 3.14 shows that, on average, the use of additive can increase the pull-off strength by approximately 170 kPa. From Figure 3.15, it is observed that as the time of conditioning samples in water increases, the pull-off strength decreases. Higher decreasing rate of pull-off strength was observed when the samples were conditioned in the water at first 6 hours, and then lower decreasing rate was shown during 6 to 48 hours. However, the effects of conditioning time on the pull-off strength for each type of aggregate are different. As can be seen from Figure 3.16, the PDC shows rapid decreasing rate in pull-off strength over the time conditioning samples in water. The Platteville shows moderate decreasing rate, whereas the Sirulian and Galena show slowly decreasing in the pull-off strength after 6 hours conditioned period.

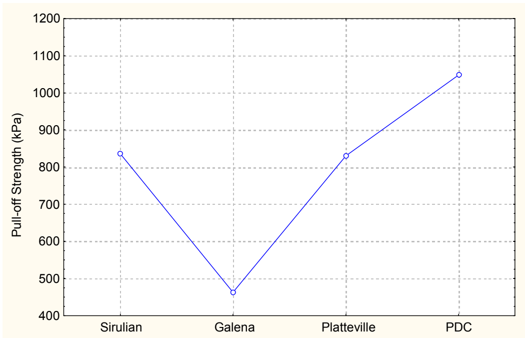


Figure 3.13 Aggregate Effect

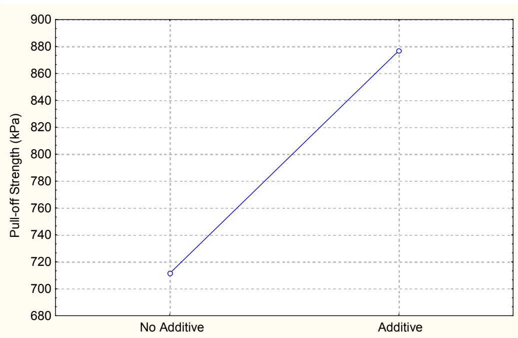


Figure 3.14 Additive Effect

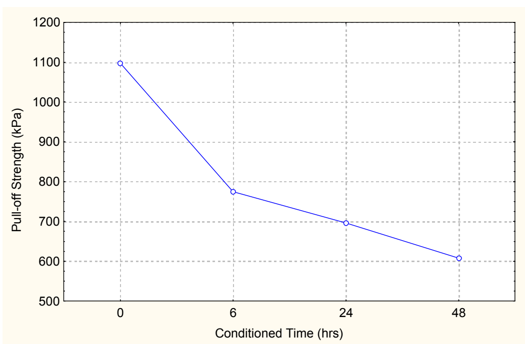


Figure 3.15 Conditioned Time Effect

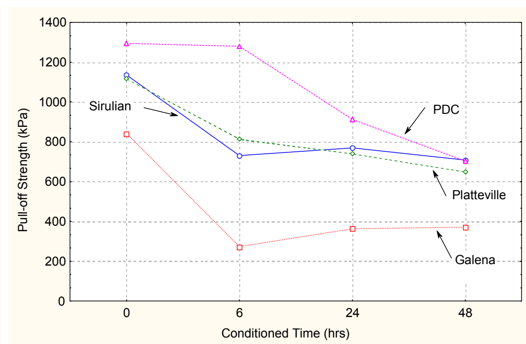


Figure 3.16 Aggregate and Conditioned Time Interaction Effect

3.4.3 Cohesion Testing

3.4.3.1 Measurement of Cohesion and Tackiness

The term "work of cohesion" is defined as the work required to produce the separation of the liquid adhesive (*24*). One of the rheological properties of adhesive, the thin film tackiness, is believed to represent the cohesion of the adhesive as it refers to the resistance of an adhesive joint to separation as long as the adhesive remains liquid (*25*). Bikerman (1960) shows the concept of tackiness test consisting of two circular, plane-parallel, solid plates with an adhesive liquid filling the space between the plates. The force is then applied to pull apart the plates in the direction of the arrow as shown in Figure 3.17. The movement in adhesive liquid is maintained when the stress (f) required to separate the plates is continually operative. He states that the tackiness is the viscous resistance of a liquid moving in a slit at a rate determined by the rate of separation of the plates. The relationship between the stress (f) and the time (t) during which the distance between the plates increased from d_0 to d_1 was derived by Stefan (*26*) as:

$$ft = \frac{3\eta a^2}{4}\left(\frac{1}{d_0^2} - \frac{1}{d_1^2}\right)$$

where f is the stress applied, t is the duration of its action, η is the viscosity of adhesive, a is the radius of specimen, d_0 is the initial thickness of adhesive layer, and d_1 is the thickness after time interval t.

In 2001 a new approach, called the Tack Test system controlled by the Dynamic Shear Rheometer, was developed by the Paar Physica USA in collaboration with the University of Wisconsin-Madison to measure the stickiness of asphalts. The measuring system can move up with a well-defined speed (0.01 mm/s) and measure the force acting between the adhesives and the measuring system surface. The force applied and the time of separation are measured and the stickiness or tack factor (C_T) of asphalt can be calculated by integrating the area under the force vs. time curve. The tack factor can represent the energy of separation (w) of the adhesive joints which can be calculated by the following equation:

$$w = 1/A \cdot \int F \cdot v \cdot dt = d \cdot \int \sigma \cdot d\varepsilon$$

where F is the force applied, t is the measuring time, A is the contact area of adhesive joint, d is the specimen thickness, and v is the speed of separation.

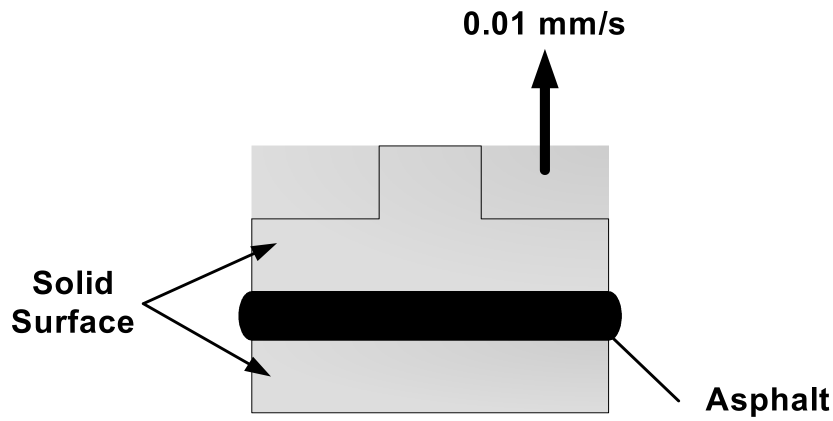


Figure 3.17 Schematic of Adhesive Joint

The cohesion or the tackiness of asphalt binder is an important mechanism that causes the failure in the asphalt-aggregate bond. Bikerman also (1960) states that the separation or the rupture of the bonding usually occurs within the adhesive layer. His study claims that the possibility of cohesive failure is much greater than adhesive failure unless the bond between the adhesive and solid surface is extremely weak. Figure 3.18 shows the explanation based on the probability of failures in true adhesion. This statement is supported by observing the failure surface of the asphalt mixture that is obtained from the Tensile Strength Ratio test (TSR). As shown in Figure 3.19, the cohesive failure of asphalt can be observed as the main failure mechanism in the asphalt mixtures. This observation could be confirmed for hundreds of specimens tested in the laboratory.

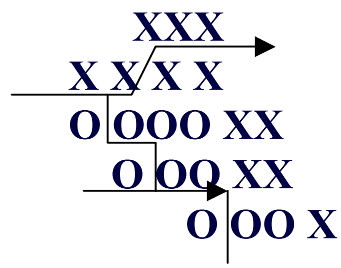


Figure 3.18 Probability of Failures in True Adhesion (*25*)

Figure 3.19 TSR Failure Surface of Asphalt Mixtures

3.4.3.2 Experimental Procedure

A tack factor of the binder can be calculated from an area under the curve of a plot of the force applied to pull apart the specimen versus the measuring time. For this study, a Thin Film Tack test of various asphalt binders was conducted: 1) to investigate the repeatability of the test, 2) to evaluate the effect of the temperature on the tack factor, and 3) to evaluate the effect of polymer and anti-strip additives on asphalt cohesion (tackiness).

In the first study, the PG 58-28 asphalt binder was measured at 25C for 3 replicates accordingly to investigate the repeatability of the test. Secondly, PG 58-28 and modified PG 64-28 with Elvaloy were measured at different temperatures, i.e., 16C, 28C, 40C, 52C, and 64C, to determine the effect of temperature on the tack factor. Finally, PG 58-28, PG 58-28 with anti-stripping additive, PG 64-28 with various types of polymer, i.e., SB, SBS, and Elvaloy were measured at given G* (1.2 MPa) to determine the effect of different additives.

3.4.3.3 Evaluation of Repeatability of Thin Film Tack Test Using the Rheometer

Figure 9 clearly shows that the tack test of asphalt binder PG 58-28 at 25C is very repeatable. The tack factors calculated from each replicate as shown in Figure 3.20 range between 209 and 220 s.N, which is a 5 percent range of the average. This range is reasonable and could possibly be improved with training and better control of thermal history.

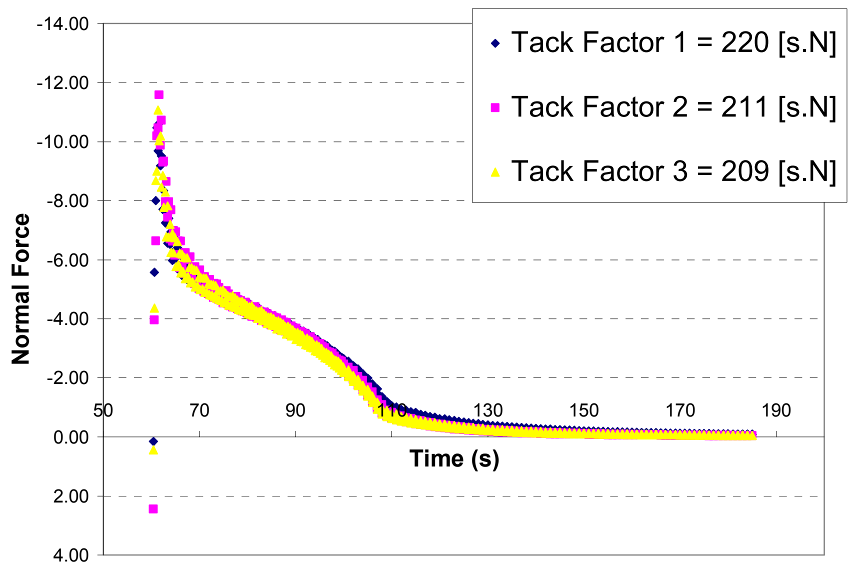


Figure 3.20 Repeatability of the Thin Film Tack test

3.4.3.4 Effect of Temperature on the Thin Film Tack Test

The effect of the temperature on the tack factor for two binders is shown in Figure 3.21. It can be seen that the temperature significantly affects the tack factor or the tackiness of asphalt binder. As the temperature increases, the tackiness of the binder decreases. Additionally, it can be observed that the polymer modification used show a positive effect at all temperatures. It should be noted that the tack factor is sensitive to the initial film thickness. For the tested binders, it was difficult to reach exactly 0.3 mm at 16C and 64C. The thicknesses were however very close to 0.3 mm (±0.07) that we assumed to be closed enough to be used in the analysis. The binder is too stiff at 16C resulting in thicker initial film thickness, and too soft at 64C resulting in thinner initial film thickness. At 16C, the rheometer reaches its maximum normal force capacity while at 64C; the normal force resolution is affecting the control to reach 0.3 mm. Therefore, this test would be standardized a careful look at capabilities of existing rheometers commonly used for asphalt which should be considered in relation to the possible initial film thickness and normal forced required.

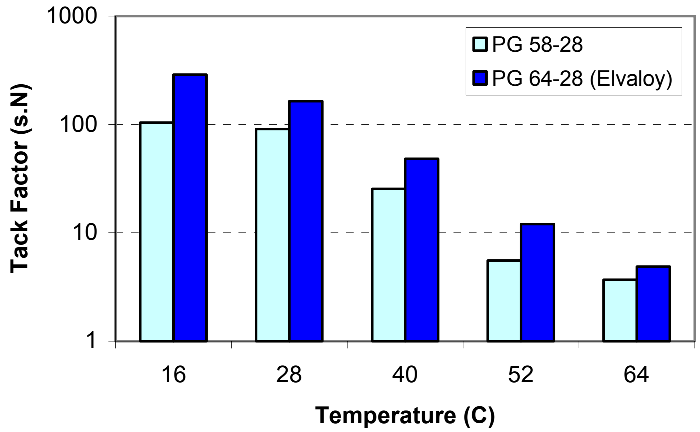


Figure 3.21 Effect of Temperature on Tack Factor

3.4.3.5 Effect of Polymer and Anti-Stripping Additives on Asphalt Cohesion

Field experiences as well as laboratory studies have reported improvement in moisture damage resistance of HMA. It has been hypothesized that such improvements result from better adhesion but it could also be related to better cohesion. Figure 3.22 shows the results of testing five asphalts that include unmodified and modified asphalts with SB, SBS, Elvaloy, and an anti-stripping additive. The results show a significant change in cohesion of asphalts because of incorporating additives. The asphalt modified with Elvaloy shows a tack factor of 148 s.N which is more than 250 percent of the unmodified asphalt. It is important to note that the asphalts are tested at a given G* value of 1.2 MPa by changing temperatures. It is also observed that the anti-stripping additive did not improve the cohesion but resulted in a slight decrease relative to the unmodified asphalt. The improvement caused by the anti-stripping additive that was clearly observed in the PATTI results (Figure 3.12 and 3.14) is mainly an improvement in adhesion rather than cohesion properties. Results of the Thin Film Tack test are very promising and show a good potential that this test could effectively measure improvements in cohesion properties of asphalts.

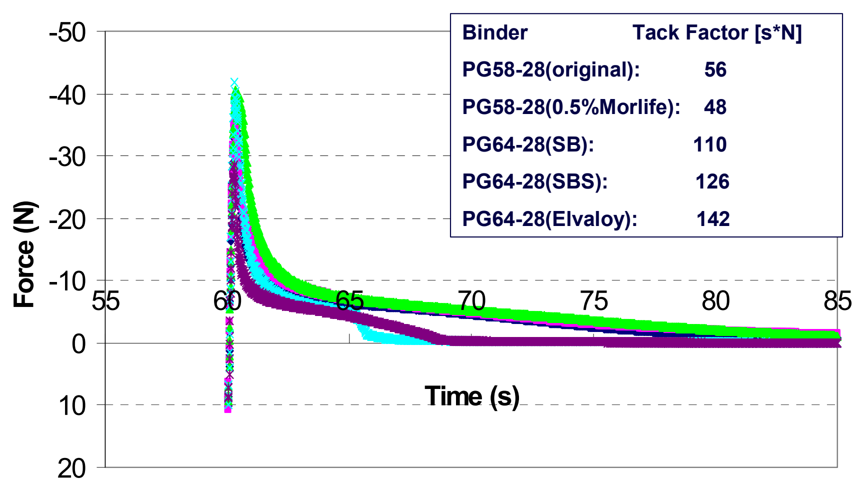


Figure 3.22 Comparison of Tack Factor among Materials at Equal G* (1.2 MPa)

3.4.4 Relationship between Adhesion Test by PATTI, Thin Film Tack Test, and Standard Tensile Strength Testing (AASHTO T-283)

Based on the adhesion test results conducted by the PATTI, it is observed that most of the failures of the dry specimen are cohesive failures, while most of the failures of the water-conditioned specimen are adhesive failures. Therefore, if the PATTI and the Thin Film Tackiness are truly measuring indicators of moisture damage, the tensile strength of unconditioned asphalt mixtures should correlate with the cohesion property of asphalt binder. The tensile strength of the conditioned asphalt mixtures, on the other hand, should correlate with both adhesion and cohesion properties of asphalt binders. The adhesion and cohesion, in this study, were measured by the PATTI test and the Thin Film Tack test, respectively.

To measure adhesion, the ratio of the pull-off strength of the conditioned specimen to the unconditioned specimen of different kinds of asphalt binder was determined. The pull-off strength ratio was then correlated to the TSR of asphalt mixtures produced with the same asphalt binders. Asphalt binders: AR 4000 (PG 64-28), modified AR 4000 (modified PG 64-28), AR 8000 (PG 70-28), and modified AR 8000 (modified PG 70-28) were used, and a chemically treated crumb rubber was selected as the asphalt modifier. Only one aggregate surface, Sirulian, was used in this experiment. The specimen preparation and the test procedure are exactly the same as indicated in section 3.4.2. The conditioned specimens were submerged in water at 25C for 24 hours, taken out from the water and immediately tested.

To measure cohesion, same set of binders, AR 4000 (PG 64-28), modified AR 4000 (modified PG 64-28), AR 8000 (PG 70-28), and modified AR 8000 (modified PG 70-28) were measured the tack factor and then correlated to the maximum tensile strength of the asphalt mixtures.

To perform the standard tensile strength testing, four sets of asphalt mixtures were compacted by using previous four asphalt binders. The mix design variables were controlled in order to compare the performance of different binders with same mix volumetrics. A total of six specimens was prepared for each set of asphalt binder, three unconditioned and another three for conditioned specimens.

To determine the correlation between the tensile strength of unconditioned specimens and the tack factor, the average maximum tensile strength (unconditioned specimens) and the average of two tack factors for each asphalt binder were measured and are recorded in Table 3.8. The correlation of the dry tensile strength and the tack factor is shown in Figure 3.23. In addition, to determine the correlation between the tensile strength of conditioned specimens, the tack factor and the adhesion strength by PATTI, the maximum tensile strength (conditioned specimens), the average of two tack factors for each asphalt binder, and the pull-off strength ratio (unconditioned versus conditioned) were measured and are recorded in Table 3.9. The correlation of the wet tensile strength (conditioned) and the combined function of tack factor and pull-off adhesion strength is shown in Figure 3.24.

Table 3.8 Summary of Maximum Tensile Strength of Unconditioned Specimens and Tack Factor of Related Asphalt Binder

Binder Type	Unconditioned		Tack Factor (sN)	Average Tack Factor (sN)
	Maximum Strength (kPa)	Average Maximum Strength (kPa)		
AR 4000 (PG 64-28)	630 602 614	615	49.5 49.1	49.3
Modified AR 4000 (Modified PG 64-28)	697 701 799	732	67.5 62.2	64.8
AR 8000 (PG 70-28)	1230 1156 1260	1216	183.5 197.2	190.3
Modified AR 8000 (Modified PG 70-28)	1309 1253 1279	1280	289.1 237.3	263.2

Table 3.9 Summary of Maximum Tensile Strength of Conditioned Specimens, Tack Factor, and Pull-off Strength Ratio of Related Asphalt Binder

Binder Type	Conditioned		Tack Factor (sN)	Average Tack Factor (sN)	Pull-off Strength Ratio (%)
	Maximum Strength (kPa)	Average Maximum Strength (kPa)			
AR 4000 (PG 64-28)	348 343 378	356	49.5 49.1	49.3	52.2
Modified AR 4000 (Modified PG 64-28)	483 448 533	488	67.5 62.2	64.8	50.4
AR 8000 (PG 70-28)	691 595 479	588	183.5 197.2	190.3	41.1
Modified AR 8000 (Modified PG 70-28)	836 841 965	881	289.1 237.3	263.2	27.2

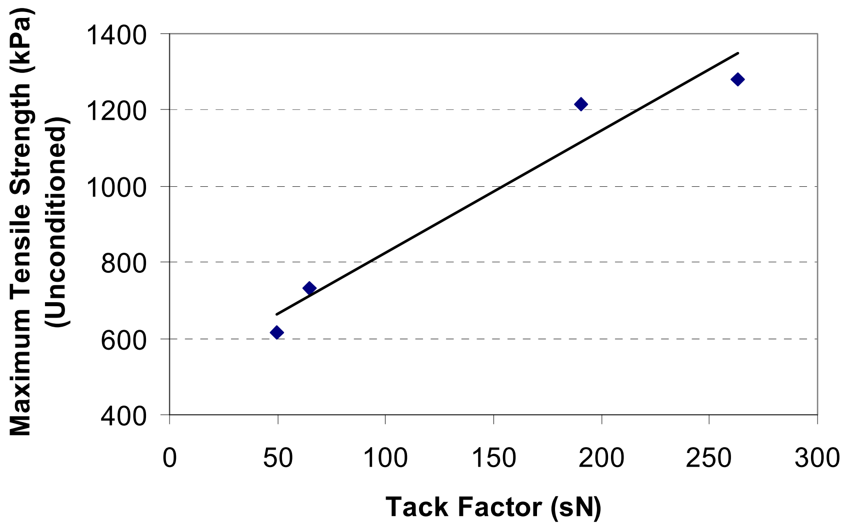


Figure 3.23 Relationship Between Maximum Tensile Strength of Mixtures (Unconditioned Specimens) and Tack Factor of Related Asphalt Binder

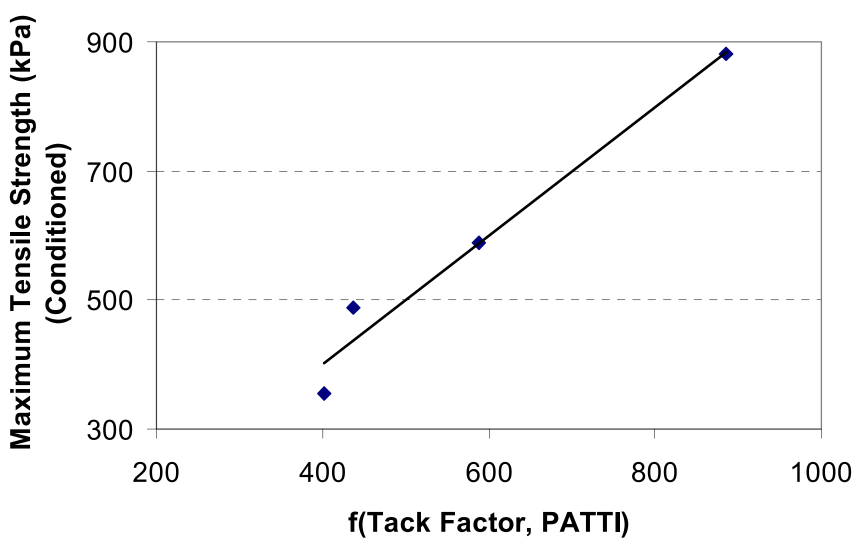


Figure 3.24 Relationship Between Maximum Tensile Strength of Mixtures (Conditioned Specimens), Tack Factor, and Pull-off Strength Ratio of Related Asphalt Binder

As shown in Figure 3.23, there exists a strong relationship (R^2 = 0.95) between the tensile strength of the unconditioned asphalt mixtures and the tack factor of related asphalt binder. This result, therefore, can support the assumption that the cohesion plays a dominant role in the bonding property of asphalt binder, and thus affects the performance of dry asphalt mixtures. Similarly, Figure 3.24 shows a strong correlation with R^2 = 0.97 between the tensile strength of conditioned specimens and a function of the tack factor and the pull-off strength measured by the PATTI. The following function was used to develop the correlation.

Tensile Strength (Wet) = 1717 – 0.62 Tack – 24.6 PATTI

These initial results, which are limited in scope, indicate that both adhesion and cohesion play significant roles in the bonding properties of asphalt binder to aggregate, and hence influence the resistance to moisture damage of asphalt mixtures as shown in Figure 3.23 and Figure 3.24.

Although the results of validation are limited to only four binders at this time, they are very promising and show that the new tests proposed could be useful tools for estimating contribution of asphalt binders to resistance of moisture damage. They also offer a procedure that clarifies of the role of cohesion and adhesion in moisture damage of HMA.

3.5 Summary

Based on the results of the study in this chapter, the following conclusions could be drawn:

- The field data that was collected from the WisDOT database indicated that using anti-stripping additive could improve the overall pavement performance, as can be seen in the PDI values.
- The database analysis also indicated that the anti-stripping additive could relieve the severity of surface raveling and rutting which are known as the pavement distress that caused by moisture damage.
- The DSR testing conducted in the laboratory study does not show important changes in the asphalt binder properties when the anti-stripping additive was used. The binder properties that were measured include storage and loss moduli, and the rutting and fatigue response using the DSR.
- The adhesion strength of asphalt binder was measured by using the PATTI device to determine the pull-off strength of asphalt binder from solid surfaces such as glass plate and aggregate surface. The asphalt binder testing with the glass plate does not show important difference in the pull-off strength when using the additive and/or when conditioning the samples in water for a period of time. This is because the water cannot penetrate into the asphalt-glass interface. As a result, the cohesion failure (failure within asphalt) was observed in all asphalt-glass plate samples.
- For the asphalt applied to aggregate surfaces, the aggregate types, anti-stripping additive, and the time of conditioning the samples in water have significant

effects on the pull-off strength of asphalt binder. In addition, the interaction between the aggregate type and conditioning time was found to have a significant effect. The decreasing rates of pull-off strength when conditioning the samples in water over a period of time are different for each aggregate type, which indicates important aggregate source dependency.

- The tackiness values of different asphalt binders were found to be sensitive to temperature and asphalt modifiers. Higher temperature results in lower tackiness. In addition, at the same temperature, asphalt modifiers show a significant effect on the tack factor.
- Based on limited data collected, the tests proposed show some promise in explaining mixture tension behavior. The tensile strength of unconditioned asphalt mixtures measured using standard Indirect Tension test can be explained by using the concept of cohesive failure. This was evident form the strong correlation between the maximum tensile strength of unconditioned specimens and the thin film tack factor of related asphalt binders. The tensile strength of asphalt mixtures after conditioning in water can be explained by using the concept of both adhesive and cohesive failures. This was evident by the good relationship between the maximum tensile strength of conditioned specimens and a combined function of the tack factor and pull-off strength ratio of the related asphalt binder.

CHAPTER FOUR

COST ANALYSIS

4.1 Introduction

In this chapter, the cost of additives being used and the costs associated with the requirement of testing for the mixtures were established with the help of WisDOT, and as shown in Table 4.1.

Table 4.1 Cost Lists for Additives and Predictive Testing for Mixtures

Materials	**Cost ($)** (Cost in 2001)
Asphalt Mix (Include Labor)	19.18 / ton of mix (Average for all types)
TSR Testing (Include Labor)	575 / mix design
Anti-Stripping Additive (Include Labor)	0.40-1.00 / ton of mix (0.70 for average)
Safety	0.07 / ton of mix
Maintenance (Seal Coat)	10,000 / lane mile (26 feet width)

Maintenance costs for pavement distresses that are caused by moisture damage (raveling and rutting) were also considered comparing with the list of costs above. This chapter, in other words, is to identify whether increasing the initial cost because of the anti-stripping additives will be worthwhile in the long term of pavement performance.

4.2 Cost Estimation

4.2.1 Estimated Cost for Asphalt Mix with Anti-Stripping Additive

Table 4.2 shows the cost analysis of asphalt pavement with anti-stripping additive in step by step. First, the cost for constructing the standard pavement structure with anti-stripping additive was analyzed. The design pavement life of 18 years was selected referring to the standard pavement life in Wisconsin. Since the additive was used in this analysis, two TSR testing were required (before and after adding the anti-stripping additive). A total of four TSR tests for two mix designs, upper and lower layer, were performed. The production of asphalt mixtures for one mix design can vary in use by amounts such as 5,000, 10,000, 30,000, or 75,000 ton per mix design depending on the project requirements for materials. Therefore, the material cost also varies to the amount of material required. A pavement thickness of 4.25-in (1.75-in upper layer and 2.50-in lower layer), and 26 feet lane width was the standard used in this analysis. The final cost of the pavement per length was determined as shown in Table 4.2.

Second, the cost for constructing of the typical overlay with anti-stripping additive was also analyzed. The analysis is similar to the cost of standard pavement, except that only one mix design is used due to one layer of pavement required, thus, only two TSR testing were performed (before and after adding the anti-stripping additive).

4.2.2 Estimated Cost for Asphalt Mix with Anticipated Maintenance (No Anti-Stripping Additive Used)

Table 4.3 shows the cost analysis of asphalt pavement without using anti-stripping additive. The process is similar to the cost analysis of the standard pavement structure with anti-stripping additive. The design pavement life of 18 years is still selected.

However, without using additives, the maintenance cost after a long-term period of pavement life was considered in this analysis instead. This leads to the reduction of TSR testing to be one per mix design. And the maintenance cost which assumed using the seal coat for every 5-6 years, or approximately 3 times in 18 years was taken in to the account of the analysis. The final cost was shown in Table 4.3 for different amount of mix design.

4.3 Summary

The cost estimation in Section 4.2 shows that the final cost for constructing a new asphalt pavement with anti-stripping additives is approximately the same as the cost of one without anti-stripping additives but anticipating a maintenance cost for every 5-6 years during an 18 year life cycle. In addition, the final cost for the typical overlay with anti-stripping additives shows the most economical value.

Table 4.2 Estimated Cost for Asphalt Mix with Anti-Stripping Additive

Standard Pavement Structure with Anti-Stripping Additive Design Life = 18 years	- Asphalt mix cost = \$19.18 / ton - Safety cost = \$0.07 / ton - Additive = \$0.70 / ton (Average) - TSR Testing (before and after adding anti-stripping additive) = \$1,150 / mix design The total is two mix designs 1. Upper layer – 12.5 mm, 1.75 in. thickness 2. Lower layer – 19 mm, 2.50 in. thickness			
	5,000 ton / mix design	***10,000 ton / mix design***	***30,000 ton / mix design***	***75,000 ton / mix design***
	- TSR Testing = \$0.46 / ton - Total cost = \$20.41 / ton = \$20.41 / 20 = \$1.021/ft^3	- TSR Testing = \$0.230 / ton - Total cost = \$20.18 / ton = \$20.18 / 20 = \$1.009/ft^3	- TSR Testing = \$0.076 / ton - Total cost = \$20.026 / ton = \$20.026 / 20 = \$1.001/ft^3	- TSR Testing = \$0.030 / ton - Total cost = \$19.98 / ton = \$19.98 / 20 = \$0.999/ft^3
	(1 ton = 2200 lbs, unit weight of asphalt mixture = 110 lb / ft^3, 1 ton = 20 ft^3) - Assume the pavement of 4.25 inches thickness, and 26 feet lane width			
	= \$1.021 x 26′ x 0.354′ = \$9.397 / ft **= <u>\$49,620 / mile</u>**	= \$1.009 x 26′ x 0.354′ = \$9.287 / ft **= <u>\$49,035 / mile</u>**	= \$1.001 x 26′ x 0.354′ = \$9.213 / ft **= <u>\$48,645 / mile</u>**	= \$0.999 x 26′ x 0.354′ = \$9.195 / ft **= <u>\$48,550 / mile</u>**

Typical Overlay with Anti-Stripping Additive	- Asphalt mix cost = \$19.18 / ton - Safety cost = \$0.07 / ton - Additive = \$0.70 / ton (Average) - TSR Testing (before and after adding anti-stripping additive) = \$1,150 / mix design			
	5,000 ton / mix design	***10,000 ton / mix design***	***30,000 ton / mix design***	***75,000 ton / mix design***
	- TSR Testing = \$0.23 / ton - Total cost = \$20.18 / ton = \$20.18 / 20 = \$1.009 ft^3	- TSR Testing = \$0.115 / ton - Total cost = \$20.065 / ton = \$20.065 / 20 = \$1.003 ft^3	- TSR Testing = \$0.038 / ton - Total cost = \$19.988 / ton = \$19.988 / 20 = \$0.999 ft^3	- TSR Testing = \$0.015 / ton - Total cost = \$19.965 / ton = \$19.965 / 20 = \$0.998 ft^3
	- Assume the overlay of 3.5 inches thickness, and 26 feet lane width			
	= \$1.009 x 26′ x 0.292′ = \$7.652 / ft **= <u>\$40,400 / mile</u>**	= \$1.003 x 26′ x 0.292′ = \$7.615 / ft **= <u>\$40,206 / mile</u>**	= \$0.999 x 26′ x 0.292′ = \$7.584 / ft **= <u>\$40,046 / mile</u>**	= \$0.998 x 26′ x 0.292′ = \$7.577 / ft **= <u>\$40,005 / mile</u>**

Note: Values used based on estimated costs for 2001.

Table 4.3 Estimated Cost for Asphalt Mix with Maintenance (No Anti-Stripping Additive)

Standard Pavement Structure with Maintenance (No Anti-Stripping Additive Design Life = 18 years	- Asphalt mix cost = \$19.18 / ton - Safety cost = \$0.07 / ton - TSR Testing = \$575 / mix design The total is two mix designs 3. Upper layer – 12.5 mm, 1.75 in. thickness 4. Lower layer – 19 mm, 2.50 in. thickness			
	5,000 ton / mix design	***10,000 ton / mix design***	***30,000 ton / mix design***	***75,000 ton / mix design***
	- TSR Testing = \$0.23 / ton - Total cost = \$19.48 / ton = \$0.974 ft^3	- TSR Testing = \$0.115 / ton - Total cost = \$19.365 / ton = \$0.968 ft^3	- TSR Testing = \$0.038 / ton - Total cost = \$19.288 / ton = \$0.964 ft^3	- TSR Testing = \$0.015 / ton - Total cost = \$19.265 / ton = \$0.963 ft^3
	- Assume the pavement of 4.25 inches thickness, and 26 feet lane width			
	= \$0.974 x 26′ x 0.354′ = \$8.965 / ft = \$47,333 / mile	= \$0.968 x 26′ x 0.354′ = \$8.909 / ft = \$47,042 / mile	= \$0.964 x 26′ x 0.354′ = \$8.873 / ft = \$46,848 / mile	= \$0.963 x 26′ x 0.354′ = \$8.863 / ft = \$46,800 / mile
	- Maintenance cost (Seal coat) for every 5-6 years, or approximately 3 times in 18 years = 3 x \$10,000 per lane mile = 3 x \$384.62 / mile = \$1,153.86 / mile			
	Total cost = **<u>\$48,487 / mile</u>**	Total cost = **<u>\$48,196 / mile</u>**	Total cost = **<u>\$48,000 / mile</u>**	Total cost = **<u>\$47,954 / mile</u>**

Note: Values used based on estimated costs for 2001.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results and analysis of this study, the following points provide a summary of findings:

1) Based on the results from the database analysis, this data set shows no relationship between TSR and the field pavement performance as measured by the PDI. In addition, the data could not be used to find a relationship between the TSR and specific pavement distresses that are known to be related to the moisture damage (surface raveling and rutting).
2) Aggregate mineralogy does not show a relationship to the pavement performance. The pavement performance could be affected by other factors such as the production and construction of the mixture, asphalt binder used, and gradation, which are not fully documented in the database, such relationship could have been masked by the other factors.
3) Results from the database show that there is an effect of using anti-stripping additives on the pavement performance (as measured by PDI) and also an effect on the specific pavement distresses that are related to the moisture damage (surface raveling and rutting).
4) Anti-stripping additives were not found to change the rheological properties of asphalt binders, and to improve the rutting and fatigue behavior of asphalt binder as measured by the DSR. However, they were found to have the effect of

increasing the adhesion property of asphalt binder to selected mineral surfaces, especially when the binder bond is exposed to water.

5) Cost estimation of the pavement with anti-stripping additives is very similar to the cost of the pavement without anti-stripping additives when taking into consideration the cost of maintenance every 5-6 years of the pavement service life.

5.2 Recommendations

Based on the above findings from this study, the following recommendations are proposed:

1) The current TSR protocol adopted by WisDOT cannot be used as a quantifiable measure of moisture damage effects on pavement performance. The test results are not precise enough to allow a quantifiable relationship and the variables that can contribute to errors are difficult to control. It is thus useful only as an index of compatibility between aggregates and asphalts.
2) If the argument that TSR results provide only an index is accepted, there are other tests that are easier to run, and most likely less costly, that could provide an index value with better repeatability such as the stripping test of asphalt binder from aggregate surface (*27*), the boiling test and the ultra-sound bath. These tests could serve the purpose of determining the need or effects of anti-stripping additives with better certainty than the TSR. It is recommended that such tests be investigated and a replacement to the TSR be found. Another alternative is investigating the improvement of the TSR testing protocol to control all kinds of

variability that possibly occurs during the test. Such improvements could lead to better quantifiable test and better correlation to the field pavement performance.

3) Note that the TSR testing has been focused on testing the complete mixture. This approach, although realistic and logical in terms of simulating the total HMA system, is too complex to allow differentiating between the role of asphalt binders and the role of aggregates in damage. For determining fundamental bonding properties of asphalt binders and aggregates, which is needed particularly for modified asphalts, further research should be continued to study the roles of asphalt binders and aggregates separately using tests such the the PATTI test and the Thin Film Tackiness, which were explored in this study. .

4) Limited experiments in this study have shown that equipment is available to measure cohesion of asphalts and adhesion to various surfaces. Such tests could help in identifying asphalt sources that are prone to moisture damage when used with Wisconsin aggregates. These tests also measure possible low cohesion strength of asphalts and thus could explain low moisture resistance.

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